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LOW-RATE COMBUSTION IN FUEL BEDS OF HAND-FIRED FURNACES

BY

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AND

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LOW-RATE COMBUSTION IN FUEL BEDS OF HAND-FIRED FURNACES.

By Henry Kreisinger, C. E. Augustine, and S. H. Katz.

INTRODUCTION.

This paper presents the results of a study of the processes of combustion in the fuel bed of hand-fired furnaces when burning coal at such low rates of combustion as are used in house-heating apparatus. The study is an extension of the work reported in Technical Paper 137[a] which covers the higher rates of combustion, such as are used in burning coal under power plant and locomotive boilers. That report deals with rates of combustion of 20 to 180 pounds of coal per square foot of grate per hour, whereas this paper covers the rates below 20 pounds. The same apparatus and largely the same methods were used as in making the experiments with high rates of combustion. Therefore only the most important features of these are described in this paper; for fuller details the reader is referred to the report mentioned.

ACKNOWLEDGMENT.

Acknowledgment is due E. T. Gregg and F. H. Moellenhoff, junior chemists of the Bureau of Mines, who analyzed most of the gas samples and assisted with the tests.

COMBUSTION OF COAL.

In a hand-fired furnace about one-half of the combustion takes place in the fuel bed, and one-half in the combustion space. The burning fuel bed acts principally as a gas producer and a gas retort; in it the solid fuel is gasified by the partial combustion of the fixed carbon and by the distillation of the volatile matter. The gases rising from the fuel bed contain at times as much as 32 per cent combustible, and no free oxygen to burn it. Hence, to burn these gases, air must be admitted over the fuel bed and mixed with the combustible, and the mixture burned in the combustion space.

Of the air necessary for complete combustion of the fuel only about one-half can be supplied through the grate; the other half must be supplied above the fuel bed. If attempt is made to force more than this amount of air through the grate, only the rate of

[a] Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces, 1916, 76 pp.

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gasification of coal in the fuel bed is increased, while the degree of completeness of combustion as indicated by the composition of the gases leaving the fuel bed remains the same. The combustion can be completed only in the combustion space by adding enough air over the fuel bed and mixing it with the combustible. In other words, the processes in the fuel bed determine the rate and the processes in the combustion space the completeness of the combustion. In a general way, it can be said that in burning coal one-half of the combustion takes place in the fuel bed and one-half in the combustion space.

The preceding statement holds good for bituminous coal, anthracite, and coke, burned at ordinary and high rates of combustion. For low rates of combustion such as are frequently used in house-heating furnaces the process of combustion in the fuel bed is somewhat more complete and the gases rising from the fuel bed contain smaller percentages of combustible gases.

SCOPE OF EXPERIMENTS.

In this paper are given the description and the results of a series of tests made in an experimental hand-fired furnace. The tests were divided into three groups according to the method of charging the fuel and of feeding the air under the grate.

In the tests of the first group air was fed under the grate at a uniform rate, and the fuel was charged in small quantities at short intervals as is done in firing coal under power-plant boilers. The object of charging the fuel in this way was to make tests at low rates of combustion comparable with those made at high rates and reported in Technical Paper 137[a]. The rates of combustion used in these tests were 10, 6, and 3 pounds of fuel per square foot of grate per hour. Two nearly constant thicknesses of fuel bed, 6 and 12 inches, were used for each rate of combustion. The fuels used were Pittsburgh coal, anthracite, metallurgical coke, and semicoke.

The tests of the second group were made under similar conditions as regards feeding of air, but the fuel was charged in large quantities at long intervals to simulate the feeding of coal in house-heating apparatus. On account of the large charges the thickness of the fuel bed could not be kept constant, but varied from 12 to 6 inches. The tests were made at rates of combustion of 10, 6, and 3 pounds of fuel per hour, and with Pittsburgh coal only. Special attention was given to the distillation of volatile matter, and the changes in the condition of the fuel bed during the long firing cycles.

In the tests of the third group all access of air through the grate was completely shut off, the object being to determine whether the fire

[a] Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces, 1916, 76 pp.

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can be kept burning for any length of time when the ash pit is tightly closed, and under what conditions the fire could be kept over night when using different kinds of fuels. These tests were made with Pittsburgh coal, anthracite, and coke, and with fuel beds 12 and 18 inches thick.

The observations made during the tests consisted mainly of analyses of gas samples and measurements of temperatures at various heights in the fuel bed. The apparatus with which the tests were made was a hand-fired laboratory furnace having a grate 1 square foot in area. This type of furnace was selected for these investigations because with it all the conditions could be easily controlled, and the important observations, such as the sampling of the gases and the measurement of temperatures, could be made accurately.

THE FUELS.

All of the fuels used in the tests were carefully sized by crushing and screening. Only the coal passing over a 1-inch and through a 1½-inch square mesh screen was used. The analyses of the fuels are given in the following table:

TABLE I.—*Analyses of coals used in the tests.*

	Coke.	Semi-coke.	Anthracite.	Upper Freeport or Pittsburgh screenings.
Proximate analysis of coal as received:				
Moisture.....per cent..	1.51	3.85	3.43	1.84
Volatile matter.....do....	1.58	10.61	5.20	35.40
Fixed carbon.....do....	86.07	67.70	79.91	51.08
Ash.....do....	10.84	17.84	11.46	11.68
Ultimate analysis of dry coal:				
Hydrogen.....per cent..	.51	2.36	2.51	5.06
Carbon.....do....	86.00	72.96	82.64	74.38
Nitrogen.....do....	1.08	1.83	.86	1.45
Oxygen.....do....	.54	3.12	1.37	4.78
Sulphur.....do....	.86	1.18	.75	2.43
Ash.....do....	11.01	18.55	11.87	11.90
Calorific value per pound as received.....B. t. u.	12,528	11,378	12,800	13,201

SUMMARY OF RESULTS AND CONCLUSIONS.

As previously stated, the fuel bed of a hand-fired furnace acts principally as a gas producer and gas retort; that is, the processes taking place in the fuel bed consist mainly of the gasification of the solid fuel. The oxygen flowing up through the grate is all used as it passes through the first 3 or 4 inches of the fuel bed. The products of combustion in this part of the fuel bed are largely CO_2, and a smaller percentage of CO. At a height of 3 to 4 inches from the grate the CO_2 content of the gases reaches a maximum of 12 to 18 per cent. As the CO_2 passes through the upper layers of the fuel bed it is reduced by contact with the hot coal to CO, which with the combustible gases

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distilled near the surface of the fuel bed constitutes 16 to 30 per cent of the gases rising from the fuel bed.

The ratio of the weight of air that can be supplied through the grate to a pound of coal gasified remains constant at about 7 to 1. This ratio holds over a very wide range of rate of gasification. The faster the air is supplied the faster the fuel gasifies, the combustible content of the gases at the surface of the fuel bed remaining nearly constant. Therefore the amount of air supplied through the grate determines only the rate of combustion and not its degree of completeness. The rate of combustion in house-heating apparatus can be regulated only by control of the supply of air through the grate, which is done largely by manipulating the damper in the ash-pit door.

For the complete combustion of 1 pound of average coal about 14 pounds of air are necessary; however, as only 7 pounds of air per pound of coal can be supplied through the grate, another 7 pounds must be supplied over the fuel bed in order that the gases rising from the fuel bed may be completely burned. As, roughly, one-half of the combustion process takes place in the fuel bed and one-half in the combustion space, the addition of air above the fuel bed for completely burning the gases and preventing smoke is essential. This additional air should be introduced close to the surface of the burning fuel and, if possible, in many fine streams to facilitate its mixing with the combustible rising from the fuel bed.

The process of combustion in the fuel bed is essentially the same whether firing is in small quantities at short intervals or in large quantities at long intervals. During the distillation period the percentage of combustible in the gases rising from the fuel bed is larger than it is after the volatile matter has all distilled, because during this period the fuel bed acts both as a gas producer and as a gas retort, whereas after distillation has ceased the fuel bed acts only as a gas producer. Therefore, while distillation is going on more air must be supplied over the fuel bed to burn the gases completely than after distillation has ceased. This requirement for a variable air supply over the fuel bed makes smokeless and economic burning of soft coal in hand-fired furnaces difficult. At low rates of combustion a large part of the combustible rising from the fuel bed is in the form of tar and soot, which are difficult to burn because they require a greater concentration of oxygen than is usually found in the furnace gases.

When the air supply through the grate is completely shut off it is very difficult to keep the fire going overnight, particularly when burning anthracite or coke. When it is desired to keep fire with these fuels over night, the fuel bed should be built up to at least 12 inches and a small amount of air must be admitted through the grate. With the commercial house-heating apparatus enough air to keep the fire going may leak into the ash pit when the ash-pit door is closed.

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Enough air to maintain combustion will not enter the fuel bed from the top surface.

As the gases rising from the fuel bed contain a large percentage of carbon monoxide (CO) it is not advisable with hot-air furnaces to close entirely the damper in the smoke pipe, if there is one, because

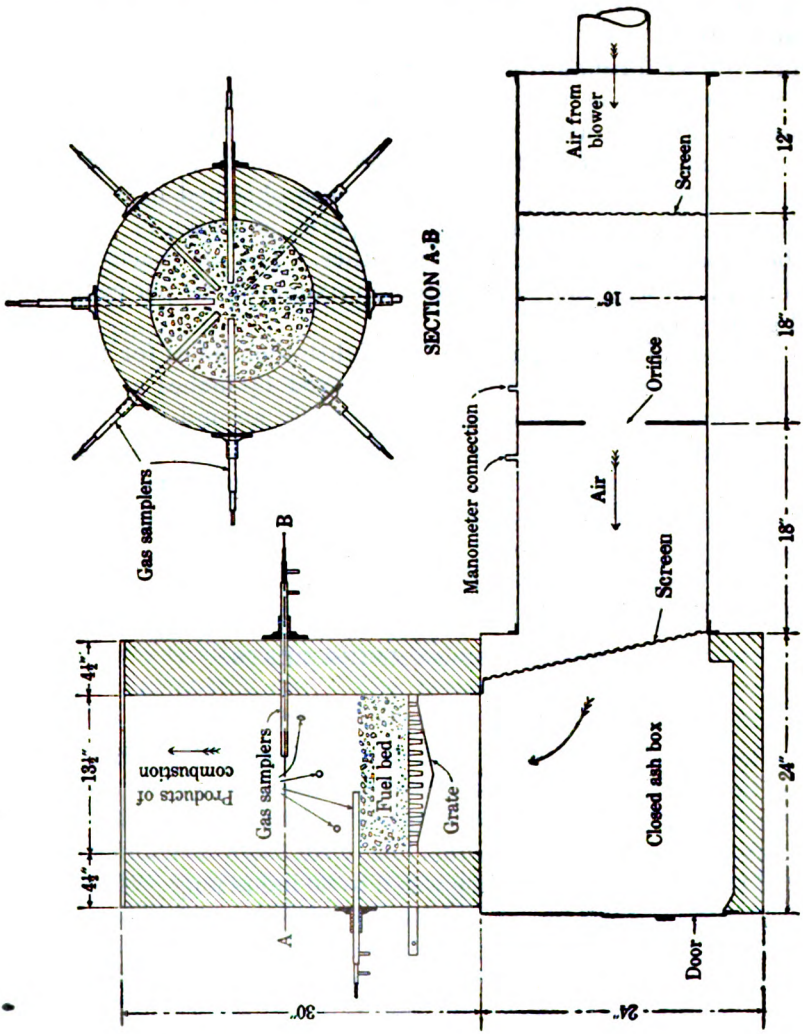

FIGURE 1.—Sections through experimental furnace.

the poisonous carbon monoxide may escape through defective joints into the air jacket and enter the rooms.

DESCRIPTION OF THE APPARATUS.

The tests were made in a hand-fired laboratory furnace specially designed for these investigations. A cross section of the furnace and its accessories is shown in figure 1. It consists mainly of a steel

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cylinder lined with a layer of fire brick 4½ inches thick. This cylinder, which forms the furnace proper, is set on an air-tight, rectangular, steel ash box. The box is provided with an air-tight door for removing the ashes. The air supplied through the grate passes into the ash box, under small pressure, through the adjoining orifice box, and is measured by means of the orifice. All joints on the apparatus are air-tight.

The cylinder forming the furnace is 30 inches high and 13½ inches in diameter inside of the fire-brick lining, making the grate area 1 square foot. The grate is nearly as large as the grate in small house-heating apparatus, hence the results obtained with the experimental furnace are directly comparable with those obtained in commercial apparatus. The grate is made in two parts, and each of the halves can be rocked independently of the other. The air spaces are one-half of an inch wide and constitute approximately 60 per cent of the total grate area.

In the wall of the furnace are five-eighth-inch holes for the insertion of gas samplers. The holes are spaced 1½ inches apart in the vertical direction and are distributed radially around the furnace as shown in figure 1. The same holes were used for measurements of temperatures in the fuel bed. When the holes were not being used for the sampling of gases or the measuring of temperatures they were stopped with a cap fitted over the mouth.

The fuel was charged through the opening at the top of the furnace, and through which the products of combustion left the apparatus.

METHOD OF RUNNING TESTS.

DURATION OF TESTS.

The length of tests varied from 5 to 30 hours, depending on the rate of combustion and the nature of the test. The tests of the first and the second group, which were made to obtain data for the study of processes of combustion in the fuel bed, were 5 to 8 hours long. In the tests of the third group the time was 6 to 30 hours long. These latter tests were made to determine whether the fire could be kept burning when the supply of air through the grate was completely shut off, and what were the conditions necessary to keep the fire burning overnight. In case the fire went out, the test was stopped; this accounts for the shorter tests of this group.

STARTING AND CLOSING THE TESTS.

Before starting the test, the fuel bed was built to the desired thickness and the furnace was heated. This preparation usually took 30 to 60 minutes, during which period the fuel was burned at a rate of 20 to 30 pounds per hour. The grate was then shaken, all the ash was removed from the ash box, and the test was started.

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The tests of the first and second group were closed with the fuel bed of the same thickness as it was at the start. The grate was shaken and the ash was removed from the ash box and weighed. The fuel on the grate was allowed to burn out and the clinkers left on the grate were taken out and weighed. The tests of the third group were stopped whenever it was definitely decided that the fire had gone out, or when, after 24 to 30 hours, the fire could be brought, in 15 to 30 minutes, to a rate of combustion of 10 pounds per hour by supplying sufficient air under the grate.

MEASUREMENT OF AIR SUPPLY.

The air supplied through the grate was measured with an orifice as the air was passing into the ash box. The pressure drop through the orifice was obtained with a recording differential hydrogage. The weight of air was computed from experimental values determined by Durley.[a]

MEASUREMENT OF TEMPERATURES.

In the tests of the first and second groups the temperatures in the fuel bed were determined with an optical pyrometer through the holes used for sampling gases. Before the measurements were made the grate was shaken to remove the excess of ash from the fuel bed. The temperature was measured by sighting with the pyrometer into small tunnels made in the fuel bed with a rod. To prevent the gases from flowing out of the furnace during the temperature measurements, the opening was closed on the outside with a thin clear glass plate fitted into a special cap. The presence of the glass made no appreciable difference in the reading of the temperatures. The temperatures were not taken simultaneously at all points, but in rapid succession, starting with the hole nearest to the grate. On the average, the readings at the different holes were taken about 30 seconds apart.

In the tests of the second group the temperatures of the freshly fired coal were measured with three Hoskin thermocouples made of one-sixteenth-inch wires. These couples were secured in position before the firing was made. The coal was then placed on the fuel bed and, as it was heated, the temperatures indicated by these couples were recorded at definite intervals by means of a portable potentiometer. Thus the rate of heating of the freshly fired coal was obtained.

In the tests of the third group the temperatures were too low for optical pyrometer reading. Therefore, in the first three tests of this group the temperature was not determined, but the color of the coals

[a] Durley, R. J., On the measurement of air flowing into the atmosphere through circular orifices in thin plates and under small differences in pressure: Trans. Am. Soc. Mech. Eng., vol. 27, 1906, pp. 193-233.

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in the fuel bed was noted, for example, "black," or "almost black." On the last four tests of this group the temperatures were measured with a Hoskin couple having wires about one-eighth of an inch thick. The couple was inserted 8 inches into the fuel bed through the sampling holes, and the temperature was read with a portable potentiometer. The readings were taken immediately after the collection of each set of gas samples. The temperature readings through each hole were about five minutes apart, because time was required for the thick thermocouple wire to be heated to the temperature of the fuel bed.

METHOD OF SAMPLING GASES.

All gas samples were collected simultaneously with water-cooled samplers in glass receptacles over mercury. Usually three sets of samples were collected during each test. In the tests of group 1 the analyses of the three sets were averaged for each position of the gas samplers. In the tests of the other two groups the analyses of each set were kept separate, as different conditions existed in the fuel bed at the time of taking each set of samples. The duration of collecting the samples was three to five minutes.

In the tests of the first and second groups the grate was shaken and the temperature was measured two to five minutes before each set of samples was collected. With the third group of tests the grate was not disturbed at all, and care was exercised to disturb the fuel bed as little as possible.

The general scheme of collecting gas samples is shown diagrammatically in figure 2. The apparatus consisted essentially of a water-cooled sampler, two wash bottles partly filled with water, a gas container, and a suction pipe. These parts were connected together with one-fourth-inch lead pipe, and in places with one-fourth-inch copper tubing. A steam ejector kept the pressure in the suction pipe reduced and caused a continuous current of gas to flow from the furnace through the system. The copper tube leading to the wash bottle extended below the level of the water in the bottle so that the flow of the gas made itself visible by bubbling through the water. If the flow of gas stopped, the operator could notice it immediately by the cessation of the bubbling. A part of the current of gases was made to flow into the gas container by permitting the mercury to run out of it. The gas collected in the container constituted the sample that was analyzed. Before starting to collect the gas, the air in the tubing leading to the container was exhausted by opening the pinch cock *A* and closing the pinch cock *B*. A U-tube mercury monometer was connected to the suction pipe to indicate the reduction in pressure, and facilitated the control of the gas-collecting apparatus.

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COLLECTION OF TAR AND SOOT SAMPLES.

Soot and tar samples were collected only during the tests of the second group in which firings were made at long intervals. For the collection of these samples a snugly fitting glass tube was inserted

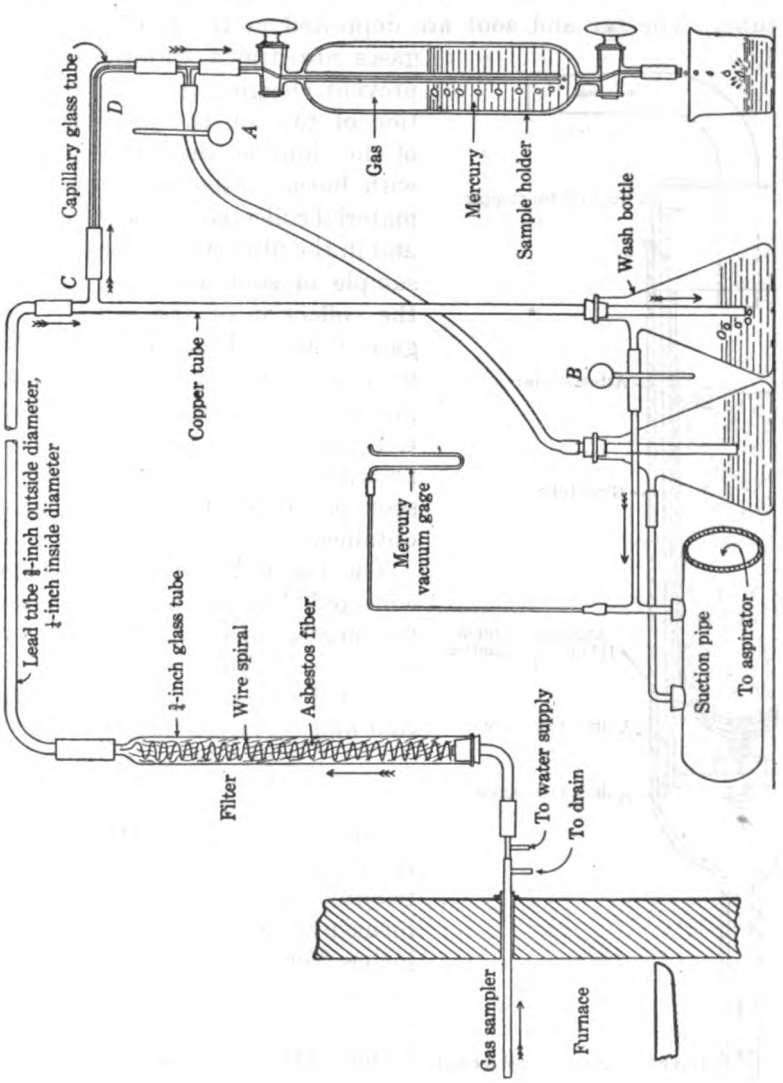

FIGURE 2.—Arrangement of apparatus for collecting samples of gases, tars, and soot. Not drawn to scale, important details are enlarged.

into the water-cooled gas sampler and a filter was placed between the glass tube and the lead-pipe connection. The tar and soot were caught in the glass tube and this filter. The filters were filled with asbestos fiber that had been previously burned to remove all combustible material. The fiber was packed around a wire spring, shown in figure 2. The object of this spring was to prevent the

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fiber from being drawn by the stream of gas to one end of the filter tube.

During the course of these experiments another filter was developed which proved to be more convenient to use. This filter, shown in figure 3, consists of a porous alundum thimble inclosed in a glass tube. The tar and soot are deposited in the thimble as the gases are drawn through it. To prevent clogging by rapid deposition of tars on the inner surface of the thimble, the latter is filled with burned asbestos fiber. The material collected in the glass tube and in the filter was the composite sample of soot and tar. During the collection of the sample, the gases flowing through the sampler were measured with a gas meter placed immediately before the suction pipe. Thus data for the expression of the weight of tar and soot per cubic foot of gas were obtained.

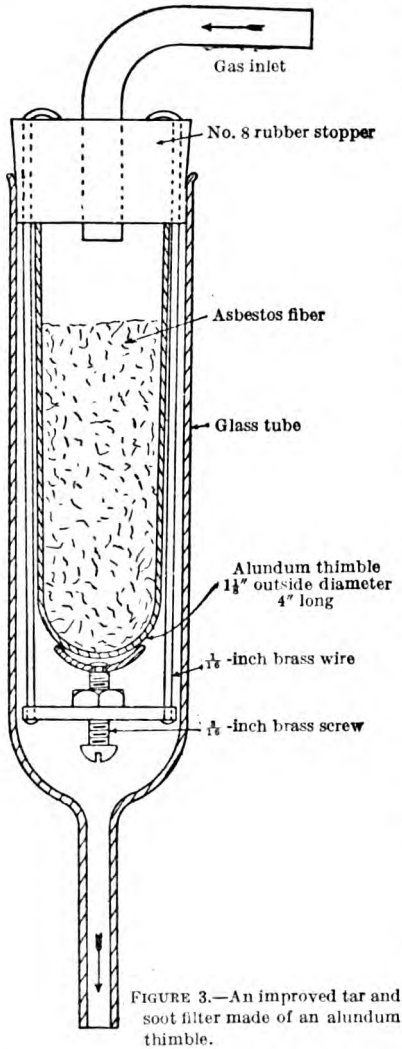

FIGURE 3.—An improved tar and soot filter made of an alundum thimble.

The tar and soot samples were collected only in the freshly fired fuel portion of the fuel bed; in the coke residue only gas samples were collected for the reason that no soot and tars were formed in it.

POSITION OF SAMPLERS.

The samplers were inserted into the furnace through the holes distributed radially in the wall of the furnace at vertical intervals of 1½ inches from the grate as shown in figure 1. That is, the first sampler was 1½ inches, the second 3 inches, and the third 4½ inches from the grate, and so on. The inlets of the samplers were placed 1½ inches from the center of the furnace. The object of distributing the samplers radially was to avoid the localization of the disturbances of the fuel bed by the samplers, and to obtain more space on the outside of the furnace for the manipulation of the samplers. With

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this arrangement the tendency to form vertical channels in the fuel bed was much less than if all the samplers had been in one vertical plane.

GAS SAMPLERS.

The samplers were water cooled in order to prevent their destruction by heat. They were made of three concentric thin-walled copper tubes. The gas was drawn through the smallest tube. The two larger tubes formed two annular spaces through which water circulated; the water entered the smaller annular space, flowed to the end of the sampler, and returned through the outer space. The joint at the end which was inserted into the fuel bed was brazed; all other joints were soldered. The sampler was provided with a sleeve which fitted tightly over the mouth of the sampling holes in the furnace wall and prevented leakage of gases around the sampler.

GAS SAMPLE CONTAINER.

The gas sample container used was a glass vessel of about 125-c.c. capacity, having the inlet tube extending almost the full length of the inside of the container. As long as the surface of the mercury was above the gas inlet, an equal volume of mercury flowed out during each equal interval of time and was replaced by the same volume of gas. The period of sampling could be regulated by controlling the flow of mercury from the container.

For convenience and safety in handling, three glass vessels were mounted on a portable wooden stand.

ANALYSIS OF GAS SAMPLES.

The samples of gas were analyzed for CO_2, O_2, CO, H_2, CH_4, and unsaturated hydrocarbons. In tests with coke and anthracite the determinations for unsaturated hydrocarbons were unnecessary.

The analyses were made with modified Hempel apparatus, the gas being analyzed over mercury. The measuring burette was water jacketed and provided with a Petterson pressure and temperature compensating tube. Determination of H_2 and CH_4 were made by the slow combustion method with heated platinum coil.

DETERMINATION OF TAR AND SOOT.

Tar was separated from soot by extraction with hot benzol in Soxhlet apparatus. The soluble part was considered tar and the insoluble combustible part was considered soot.

The deposit of tar and soot in the glass lining of the sampler was removed with asbestos fiber and benzol and added to that collected in the alundum thimble. The thimble was placed in the Soxhlet

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apparatus on a heated sand bath and extracted for some hours after the benzol ran colorless. The tar contained in the extraction flask was freed from benzol by passing dry air at room temperature through the flask until the loss was less than 3 mg. on successive weighings one day apart. The difference in weight between the flask and tar and the clean dry flask was taken as the weight of tar. While freeing the tar from benzol, some of the light oils contained in the tars were carried away with the benzol and lost.

After extraction, the alundum thimble containing the soot mixed with asbestos fiber was dried to constant weight at 105 to 110° C.; then the soot was burned off in a muffle furnace at red heat. The loss in weight due to burning, minus a correction found by running a blank, was taken as the amount of soot.

RESULTS OF TESTS OF GROUP 1.

Table 2 contains the results of the tests of the first group in which the fuel was fired in small quantities at short intervals, as is the practice in firing coal under power-plant boilers. As previously stated, four fuels were used in these tests—Pittsburgh coal, anthracite, metallurgical coke, and semicoke. Only two tests were made with the semicoke, because of insufficient supply. Two thicknesses of fuel bed were used with each of the fuels—6-inch and 12-inch. The fuels were burned at three rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

The tests are arranged: First, according to the kind of fuel; second, according to the thickness of fuel bed; and, third, according to the rate of combustion. A full explanation of each item of the table is given in the following paragraphs:

Column 1 gives the serial number of each test. The tests followed those reported in Technical Paper 137,[a] and were designated by numbers following those of the previous tests.

Column 3 gives the thickness of fuel bed during the test.

In column 4 the word "combustible" means moisture and ash-free coal.

In column 5 the duration of test is given in hours and minutes. This duration includes only the test proper and does not include the time taken in preparing the fuel bed for the test.

Column 6 gives the average pressure of air in the ash pit.

The values given in column 8 were obtained by multiplying the value in column 7 by the value in column 4 and subtracting from the product the combustible in refuse fallen into the ash pit.

In column 10 the values for the weight of air forced through the fuel bed per pound of fuel fired were obtained by dividing the values in column 9 by those in column 7.

[a] Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces: Tech. Paper 139, Bureau of Mines, 1916, pp. 27–37.

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In column 11 the values for the weight of air forced through the fuel bed per pound of combustible burned were obtained by dividing the values in column 9 by those in column 8.

In column 12 the figures represent the vertical distance of the gas sampler from the grate in inches.

Each of the values for the average composition of gases in the fuel bed, columns 13 to 20, represents the average analysis of three samples.

The temperatures in the fuel bed, column 21, at a distance from the grate given in column 12 are the averages of four readings taken with a Wanner optical pyrometer.

Column 22 gives the weight of air per pound of combustible computed from the gas analyses at the point given by column 12. The weight was computed from the following formula:

$$W=3.03C\frac{N_2}{CO_2+CO+CH_4+n(C_nH_{2n})}$$

where C is the percentage of carbon in moisture and ash-free coal, and N_2, CO_2, CO, CH_4, and C_nH_{2n} are the volume percentages of these constituents in the gases.

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TABLE 2.—*Results of tests of group 1; fuel fired in small quantities at short intervals.*

Test No.	Kind of fuel.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour by orifice.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of samples from grate.	Average composition of gases in fuel bed.								Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
												Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Ins.	*P. ct.*	*H. m.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Ins.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	°*F.*	*Lbs.*
68	Pittsburgh screenings	6	86.48	7 0	0.03	3.0	2.3	18.0	6.0	8.1	1.5	15.5	.....	3.4	2.4	0.0	0.1	78.6	2.5	1,107	11.2
											3.0	16.5	0.1	.3	5.5	.1	.5	77.0	6.2	971	8.9
											4.5	11.9	1.2	.5	10.5	1.2	1.4	73.3	14.3	964	7.6
											6.0	9.9	.9	4.7	6.6	.5	.9	76.5	8.9	.....	10.9
											7.5	4.6	.1	15.0	.3	.0	.1	79.9	.5	.....	.....
67	.....do.....	6	87.91	7 0	.04	5.9	4.9	38.0	6.5	7.8	1.5	15.6	.....	3.3	2.7	.0	.2	78.2	2.9	1,206	.....
											3.0	15.9	.....	1.6	4.7	.0	.3	77.5	5.0	1,327	.....
											4.5	13.3	.2	.2	11.0	.3	1.2	73.8	12.7	1,134	7.6
											6.0	7.2	.4	.7	19.9	1.4	3.7	66.7	25.4	997	5.9
											7.5	8.6	.7	3.0	11.4	1.6	3.2	71.5	16.9	.....	.....
66	.....do.....	6	87.91	7 0	.05	10.1	8.8	60.0	5.9	6.8	1.5	12.0	.....	7.4	2.0	.0	.1	78.5	2.1	1,336	.....
											3.0	15.0	.....	2.9	4.2	.0	.2	77.7	4.4	1,380	.....
											4.5	11.9	.1	.1	13.6	.5	1.2	72.6	15.4	1,228	7.1
											6.0	7.7	.3	.3	19.5	.8	3.8	67.6	24.4	1,102	6.1
											7.5	9.2	1.0	1.3	13.0	1.2	3.1	71.2	18.3	1,089	.....
69	.....do.....	12	86.48	7 0	.07	3.0	2.1	18.0	5.9	8.7	1.5	15.7	.....	2.5	2.9	.0	.2	78.7	3.1	1,109	.....
											3.0	15.8	.....	2.1	3.3	.1	.5	78.2	3.9	1,219	.....
											4.5	15.8	.....	.7	5.4	.1	.5	77.5	6.0	1,197	.....
											6.0	16.0	.3	.0	6.0	.1	.6	77.0	7.0	929	.....
											7.5	12.1	.2	3.0	8.3	.0	.7	75.7	9.2	972	.....
											9.0	10.8	.3	2.9	10.3	.1	1.0	74.6	11.7	.....	.....
											10.5	10.3	1.0	1.5	10.3	.3	2.0	75.6	13.6	.....	8.8
											12.0	5.5	.3	12.7	1.1	.3	.6	79.8	2.3	.....	28.3
											13.5	1.9	.0	18.3	.3	.0	.1	79.4	.4	.....	.....

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65	....do	12	87.91	7	5	.09	6.4	5.3	39.0	6.1	7.3	175	15.2	.....	4.2	1.5	.0	.1	79.0	1.6	1,237	.....
												3.0	13.7	.....	5.1	3.0	.0	.1	78.1	3.1	1,302	.....
												4.5	17.8	.0	.8	2.8	.0	.2	78.4	3.0	1,296	.....
												6.0	14.2	.0	.7	9.4	.0	.5	75.2	9.9	1,348	.....
												7.5	13.8	.0	.8	10.1	.0	.5	74.8	10.6	1,068	.....
												9.0	12.4	.1	.0	13.4	.4	.9	72.8	14.8	999	.....
												10.5	7.7	.4	.6	18.6	1.6	2.0	69.1	22.6	.....	6.3
												12.0	6.8	.1	11.3	2.3	.3	.5	78.4	3.5	.....	21.1
												13.5	7.0	.0	11.6	1.2	.1	.2	79.9	1.5	.....	.....
84	....do	12	86.48	6	4	.10	12.7	10.4	49.5	.....	.....	1.5	11.9	.....	8.1	.5	.0	.1	79.4	.6	1,229	.....
												3.0	13.3	.....	1.7	9.4	.0	.4	75.2	9.8	1,305	.....
												4.5	15.5	.....	.3	8.1	.0	.3	75.8	8.4	1,318	.....
												6.0	7.8	.....	.1	21.3	.0	.7	70.1	22.0	1,259	.....
												7.5	7.8	.....	.2	21.0	.0	.7	70.3	21.7	1,080	.....
												9.0	6.2	.0	.2	23.4	.2	1.5	68.5	25.1	1,032	.....
												10.5	2.3	.3	1.3	26.7	1.8	4.5	63.1	33.3	898	5.2
												12.0	6.3	.6	3.5	14.2	2.2	2.5	70.7	19.5	.....	7.8
												13.5	8.1	.1	7.1	6.1	.7	1.9	76.0	8.8	.....	.....
72	Anthracite coal	6	85.11	6	30	.03	3.0	2.4	19.0	6.3	7.9	1.5	12.4	.....	7.6	.9	.0	.2	78.9	1.1	1,154	.....
												3.0	16.2	.....	.3	5.6	.0	.3	77.6	5.9	1,135	.....
												4.5	16.1	.....	.0	6.8	.0	.7	76.4	7.5	1,034	9.5
												6.0	13.6	.....	3.3	5.3	.0	.8	77.0	6.1	.....	11.6
												7.5	2.7	.....	17.9	.5	.0	.2	78.7	.7	.....	.....
73	....do	6	85.11	7	30	.07	6.0	4.9	36.0	6.0	7.3	1.5	6.9	.....	12.0	2.4	.0	.0	78.7	2.4	.....	.....
												3.0	12.2	.....	4.3	5.9	.0	.1	77.5	6.0	.....	.....
												4.5	13.7	.....	.0	10.7	.0	.4	75.2	11.1	.....	8.8
												6.0	9.8	.....	1.5	14.8	.0	.9	73.0	15.7	.....	8.4
												7.5	7.5	.....	11.4	2.1	.0	.3	78.7	2.4	.....	.....
74	....do	6	85.11	7	0	.13	10.0	7.9	60.0	6.0	7.6	1.5	13.3	.....	4.1	4.9	.0	.4	77.3	5.3	1,223	.....
												3.0	13.7	.....	.2	11.4	.0	.4	74.3	11.8	1,213	.....
												4.5	10.8	.....	.0	16.2	.0	.4	72.6	16.6	1,279	7.6
												6.0	6.5	.....	.0	22.9	.1	.6	69.9	23.6	1,127	6.7
												7.5	9.2	.....	3.7	11.4	.0	1.3	74.4	12.7	.....	.....
71	....do	12	85.11	6	30	.04	3.0	2.5	19.0	6.3	7.8	1.5	13.5	.....	5.8	1.6	.0	.2	78.9	1.8	1,159	.....
												3.0	17.1	.....	.8	3.6	.0	.2	78.3	3.8	1,128	.....
												4.5	16.3	.....	.1	6.0	.0	.4	77.2	6.4	1,128	.....
												6.0	14.7	.....	.0	8.2	.0	.4	76.7	8.6	973	.....
												7.5	16.0	.....	.1	6.4	.1	.5	76.9	7.0	971	.....
												9.0	15.0	.....	.3	7.3	.0	1.6	75.8	8.9	.....	.....
												10.5	14.9	.....	.2	7.9	.2	2.9	73.9	11.0	.....	9.1
												12.0	9.2	.....	9.2	2.7	.1	1.0	77.8	3.8	.....	18.4
												13.5	9.1	.....	10.0	1.5	.1	1.1	78.2	2.7	.....	.....

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TABLE 2.—*Results of tests of group 1; fuel fired in small quantities at short intervals*—Continued.

Test No.	Kind of fuel.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour by orifice.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of samples from grate.	Average composition of gases in fuel bed.								Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
												Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Ins.	*P. ct.*	*H. m.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Ins.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*°F.*	*Lbs.*
70	Anthracite coal	12	85.11	6 40	.05	6.0	5.0	36.0	6.0	7.2	1.5	10.3	.....	9.7	1.1	.0	.1	78.8	1.2	1,202	.....
											3.0	15.7	.....	.5	7.1	.0	.1	76.6	7.2	1,286	.....
											4.5	15.1	.....	.4	8.3	.1	.2	75.9	8.6	1,263	.....
											6.0	11.2	.....	.0	15.4	.1	.4	72.9	15.9	1,251	.....
											7.5	9.0	.....	1.3	17.2	.1	.8	71.6	18.1	1,116	.....
											9.0	8.4	.....	1.5	17.5	.0	.7	71.9	18.2	1,003	.....
											10.5	5.7	.....	.1	24.3	.1	1.5	68.3	25.9	898	6.4
											12.0	8.9	.....	9.4	3.3	.1	.4	77.9	3.8	.....	18.0
											13.5	7.1	.....	12.6	.9	.0	.1	79.3	1.0	.....	.....
75	.....do	12	85.11	5 30	.15	10.0	7.8	61.5	6.2	7.9	1.5	12.6	.....	6.1	2.6	.0	.1	78.6	2.7	1,239	.....
											3.0	17.0	.....	.3	5.3	.0	.3	77.1	5.6	1,265	.....
											4.5	13.7	.....	.1	10.6	.0	.6	75.0	11.2	1,262	.....
											6.0	10.4	.....	.0	17.0	.0	.9	71.7	17.9	1,263	.....
											7.5	10.9	.....	.0	16.1	.0	.9	72.1	17.0	1,116	.....
											9.0	9.8	.....	.3	17.2	.0	.9	71.8	18.1	1,089	.....
											10.5	4.5	.....	.0	27.0	.0	1.4	67.1	28.4	1,089	6.1
											12.0	7.4	.....	.5	20.6	.0	1.5	70.0	22.1	.....	7.1
											13.5	9.0	.....	4.1	11.6	.0	1.4	73.9	13.0	.....	.....
79	Coke	6	87.65	5 0	.01	3.0	2.3	19.0	6.3	8.3	1.5	11.3	.....	7.8	1.8	.0	.1	79.0	1.9	1,116	.....
											3.0	16.0	.....	1.0	3.5	.0	.1	79.2	3.8	1,069	.....
											4.5	16.3	.....	1.1	3.2	.0	.2	79.2	3.4	993	11.9
											6.0	11.7	.....	6.8	2.3	.0	.3	78.9	2.6	926	16.5
											7.5	5.3	.....	14.6	.8	.0	.1	79.2	.9	.....	.....
78	.....do	6	87.65	5 20	.04	6.0	4.8	36.5	6.1	7.6	1.5	10.2	.....	8.2	2.3	.0	.1	79.2	2.4	1,121	.....
											3.0	13.7	.....	3.5	3.6	.0	.1	79.1	3.7	1,167	.....
											4.5	15.9	.....	.6	4.9	.0	.1	78.5	5.0	1,085	11.0
											6.0	14.6	.....	.5	8.3	.0	.2	76.4	8.5	932	9.8
											7.5	11.0	.....	6.6	3.9	.0	.1	78.4	4.0	.....	.....

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82	do	6	87.65	7	0	.04	9.9	7.8	66.5	6.7	8.6	1.5	7.4	.....	13.0	.5	.0	.0	79.1	.5	1,278	.....
												3.0	16.6	.....	2.3	2.9	.0	.1	78.1	3.0	1,365	.....
												4.5	17.5	.....	.2	4.7	.0	.2	77.4	4.9	1,267	10.2
												6.0	13.9	.....	.1	11.0	.0	.3	74.6	11.4	1,199	8.7
												7.5	14.3	.....	1.3	8.1	.0	.2	76.1	8.3	957	.....
80	do	12	87.65	6	0	.03	3.0	2.3	18.5	6.2	8.1	1.5	10.8	.....	8.3	1.9	.0	.1	78.9	2.0	1,140	.....
												3.0	15.5	.....	2.3	3.6	.0	.1	78.5	3.7	1,146	.....
												4.5	14.6	.....	1.3	5.2	.0	.1	78.8	5.3	1,127	.....
												6.0	17.3	.....	.2	4.5	.0	.2	77 8	4.7	1,081	.....
												7.5	14.2	.....	.5	8.1	.0	.3	76.9	8.4	949	.....
												9.0	14.4	.....	.1	9.0	.1	.3	76.1	9.4	938	.....
												10.5	12.4	.....	.2	12.5	.0	.5	74.4	13.0	.....	8.7
												12.0	10.4	.....	6.9	5.2	.0	.3	77.2	5.5	.....	14.5
												13.5	5.5	.....	12.8	3.1	.0	.1	78.5	3.2	.....	.....
81	do	12	87.65	6	0	.04	5.8	5.0	38.5	6.6	7.7	1.5	10.6	.....	9.5	.7	.0	.1	79.1	.8	1,260	.....
												3.0	18.0	.....	.7	3.6	.0	.1	77.6	3.7	1,246	.....
												4.5	17.9	.....	.1	4.2	.0	.1	77.7	4.3	1,233	.....
												6.0	14.0	.....	.0	11.2	.0	.2	74.6	11.4	1,170	.....
												7.5	12.9	.....	.0	12.7	.0	.4	74.0	13.1	1,074	.....
												9.0	11.9	.....	.0	14.4	.0	.5	73.2	14.9	969	.....
												10.5	8.8	.....	.1	19.8	.0	.6	70.7	20.4	950	7.2
												12.0	10.5	.....	1.2	15.0	.0	.5	72.8	15.5	.....	8.4
												13.5	11.5	.....	5.3	6.2	.0	.2	76.8	6.4	.....	.....
83	do	12	87.65	6	30	.05	10.0	8.7	65.5	6.5	7.5	1.5	6.0	.....	14.7	.2	.0	.0	79.1	.2	1,272	.....
												3.0	13.4	.....	6.1	2.1	.0	.1	78.3	2.2	1,367	.....
												4.5	17.4	.....	1.4	3.0	.0	.1	78.1	3.1	1,309	.....
												6.0	15.2	.....	0.1	8.9	.0	.3	75.5	9.2	1,338	.....
												7.5	13.9	.....	.0	11.1	.0	.3	74.7	11.4	1,252	.....
												9.0	12.5	.....	.0	13.3	.1	.3	73.9	13.6	1,189	.....
												10.5	6.8	.....	.0	23.0	.1	.4	69.7	23.5	1,026	6.8
												12.0	9.4	.....	4.0	12.0	.0	.3	74.3	12.3	898	10.2
												13.5	9.2	.....	9.3	3.5	.0	.1	77.9	3.6	.....	.....
77	Semicoke	6	78.31	6	40	.01	3.1	2.3	18.0	5.8	7.8	1.5	13.3	.....	2.4	5.8	.0	.2	78.3	6.0	964	.....
												3.0	14.7	.....	.4	6.8	.0	.4	77.7	7.2	959	.....
												4.5	13.6	.....	1.7	7.4	.0	.8	76.5	8.2	.....	9.9
												6.0	9.2	.....	9.2	2.7	.0	.5	78.4	3.2	.....	17.9
												7.5	4.7	.....	15.4	.3	.0	.1	79.5	.4	.....	.....
76	do	6	78.31	5	38	.02	10.0	7.6	34.5	3.5	4.5	1.5	3.9	.....	16.4	.6	.0	.0	79.1	.6	1,208	.....
												3.0	14.0	.....	.6	8.9	.0	.1	76.4	9.0	1,212	.....
												4.5	9.8	.....	.0	16.4	.0	.8	73.0	17.2	1,090	7.6
												6.0	7.5	.....	.5	20.0	.1	2.4	60.5	22.5	942	6.8
												7.5	8.5	.....	5.4	9.7	.1	1.6	74.7	11.4	.....	.....

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GRAPHIC REPRESENTATION OF RESULTS OF TESTS.

The curves plotted from the results of the first group of tests are shown in figures 4 to 10. These figures show the variation of the

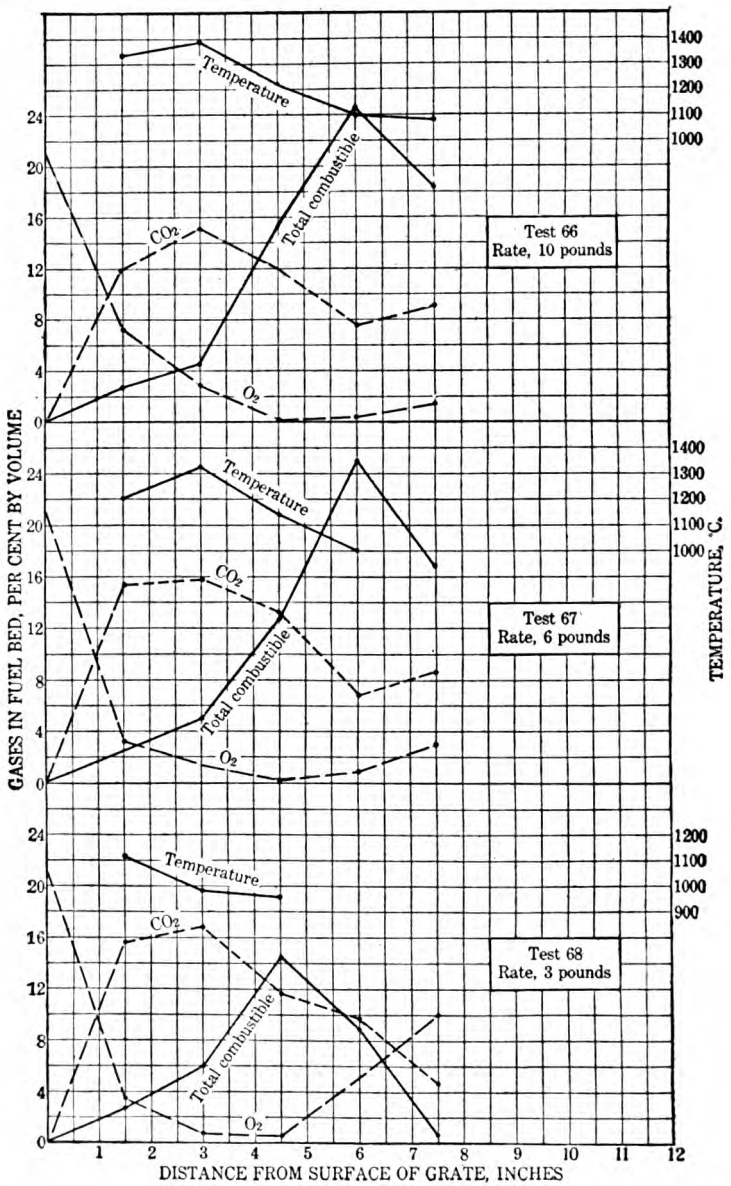

FIGURE 4.—Composition of gases and temperature in 6-inch fuel bed of Pittsburgh bituminous coal in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

different constituents of the gases as they rise through the fuel bed. The notation and the legend of each figure gives complete information

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of what the figure represents, hence the figures can be studied with little reference to the text.

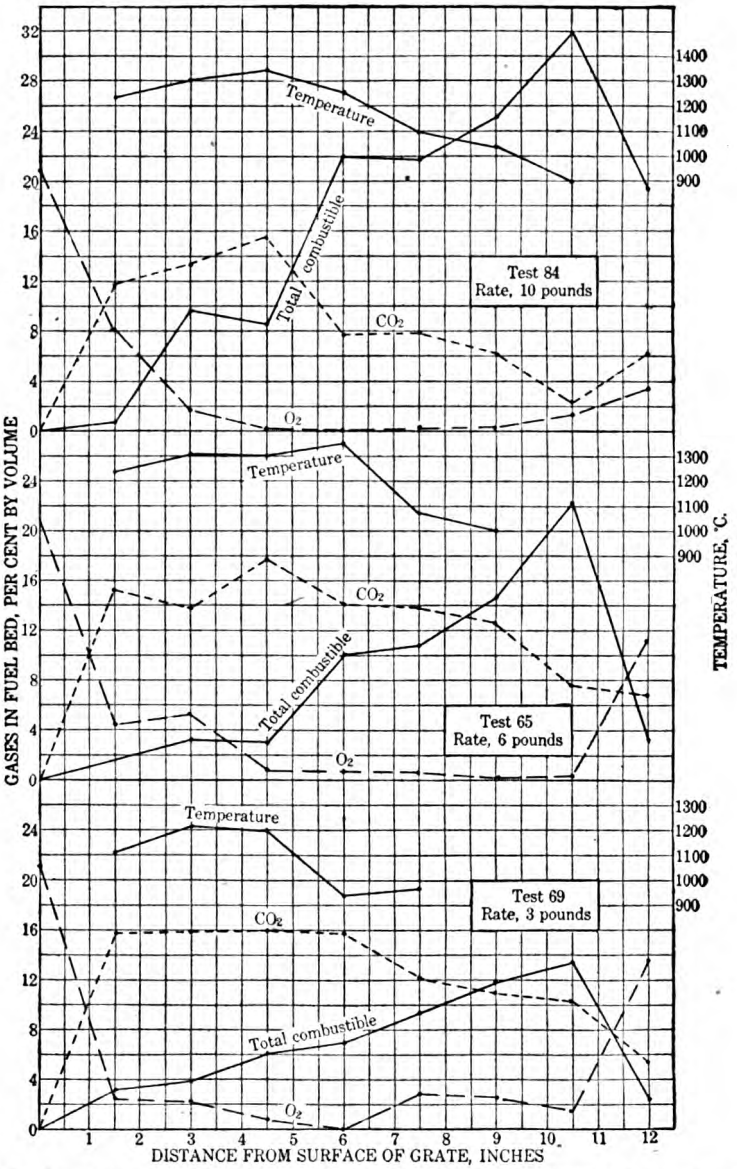

FIGURE 5.—Composition of gases and temperature in 12-inch fuel bed of Pittsburgh bituminous coal in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

DISCUSSION OF RESULTS OF FIRST GROUP OF TESTS.

PROCESSES OF COMBUSTION IN FUEL BED.

In general, the processes of combustion in the fuel bed when the fuel is burned at low rates are the same as they are when the fuel is

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burned at high rates of combustion, such as are used in firing coal under power-plant or locomotive boilers. This fact is shown by com-

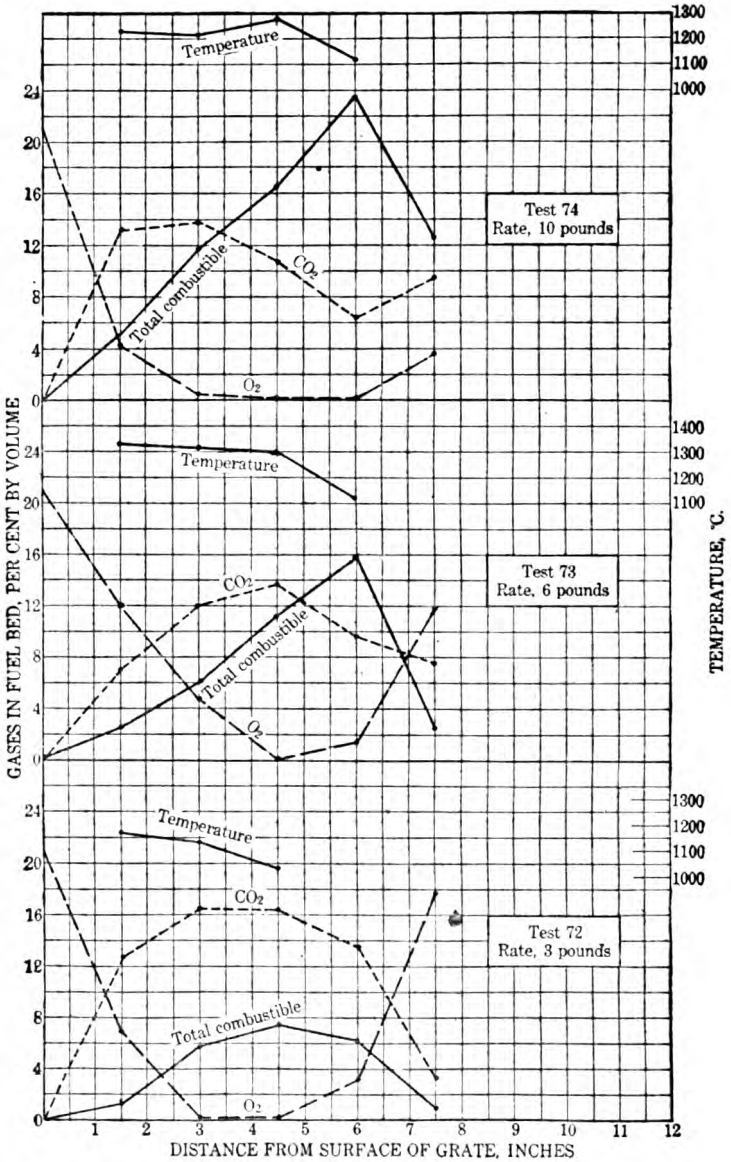

FIGURE 6.—Composition of gases and temperature in 6-inch fuel bed of anthracite coal in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

parison of figures 4 to 10 with similar figures in Technical Paper 137.[a] With a 6-inch fuel bed, the oxygen in the air supplied through the

[a] Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces: Tech. Paper 137, Bureau of Mines, 1916, pp. 39–44.

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grate is almost all used up in the lowest 3 inches of the fuel bed by burning the carbon of the coal to CO_2, only a comparatively small percentage of CO being formed. At this point the CO_2 content of the gases rising through the fuel bed reaches a maximum of 14 to 16

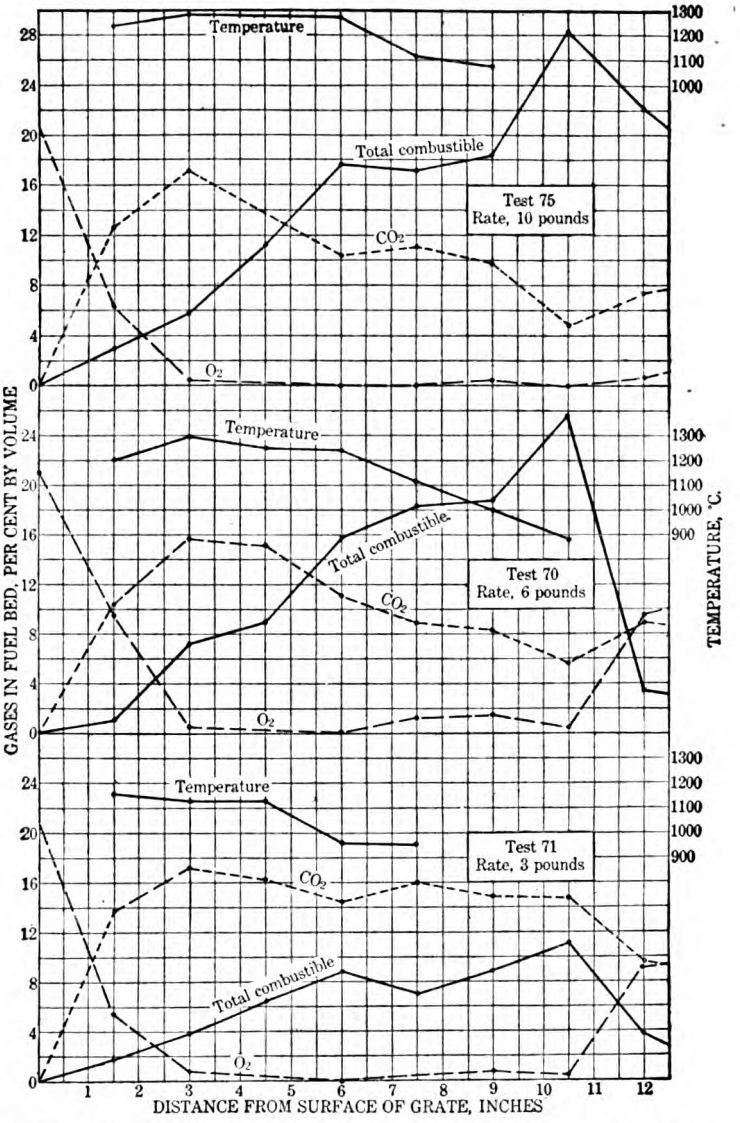

FIGURE 7.—Composition of gases and temperature in 12-inch fuel bed of anthracite coal in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

per cent. As the gases flow through the upper layers of the fuel bed the percentage of CO_2 drops and the percentage of CO increases rapidly. This change indicates that as long as there is free oxygen the carbon is oxidized to CO_2, but when the oxygen is used up, the CO_2

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acts as an oxidizing agent and is reduced to CO, which increases twice as rapidly as CO_2 disappears. The zone of reduction of CO_2 extends to near the surface of the fuel bed. Just within the top of

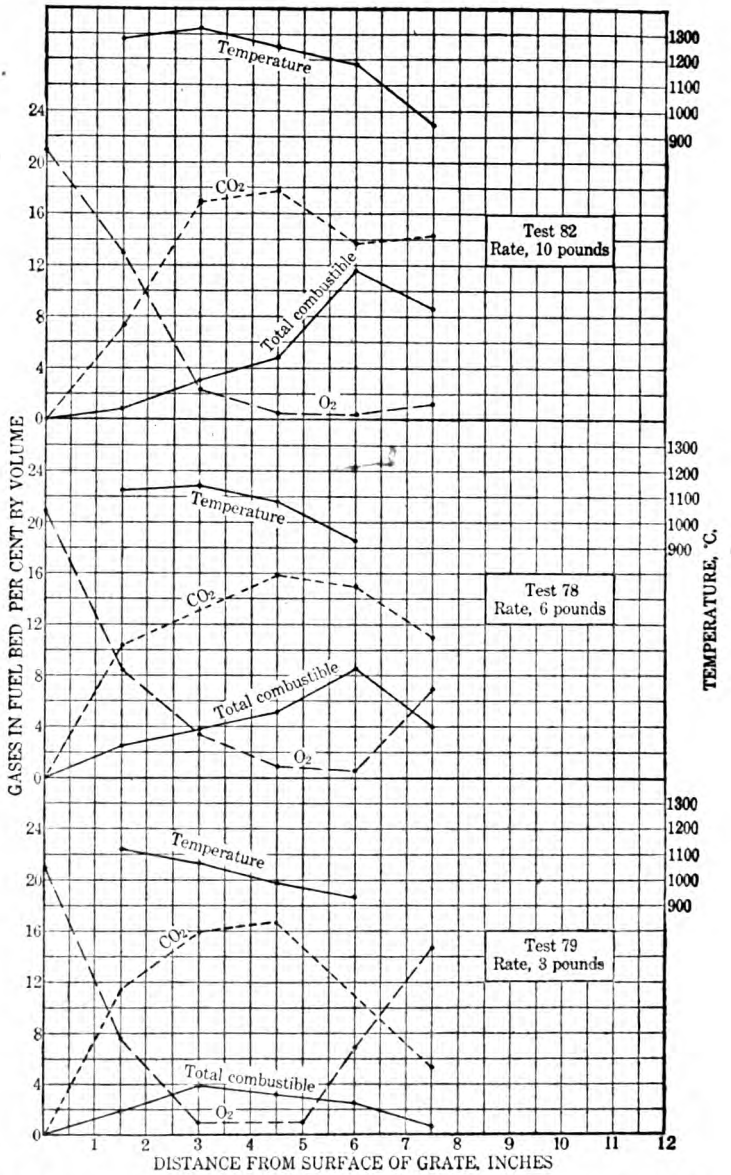

FIGURE 8.—Composition of gases and temperature in 6-inch fuel bed of metallurgical coke in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

the fuel bed the reduction of CO_2 is stopped by the presence of air which comes down along the sides of the furnace and penetrates the upper part of the bed. In the charts this infiltration of air from the

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top of the furnace is indicated by the appearance of free oxygen in the gases, the drop in CO content due to its combustion, and with the higher rates of combustion the rise in CO_2 content. With the lower

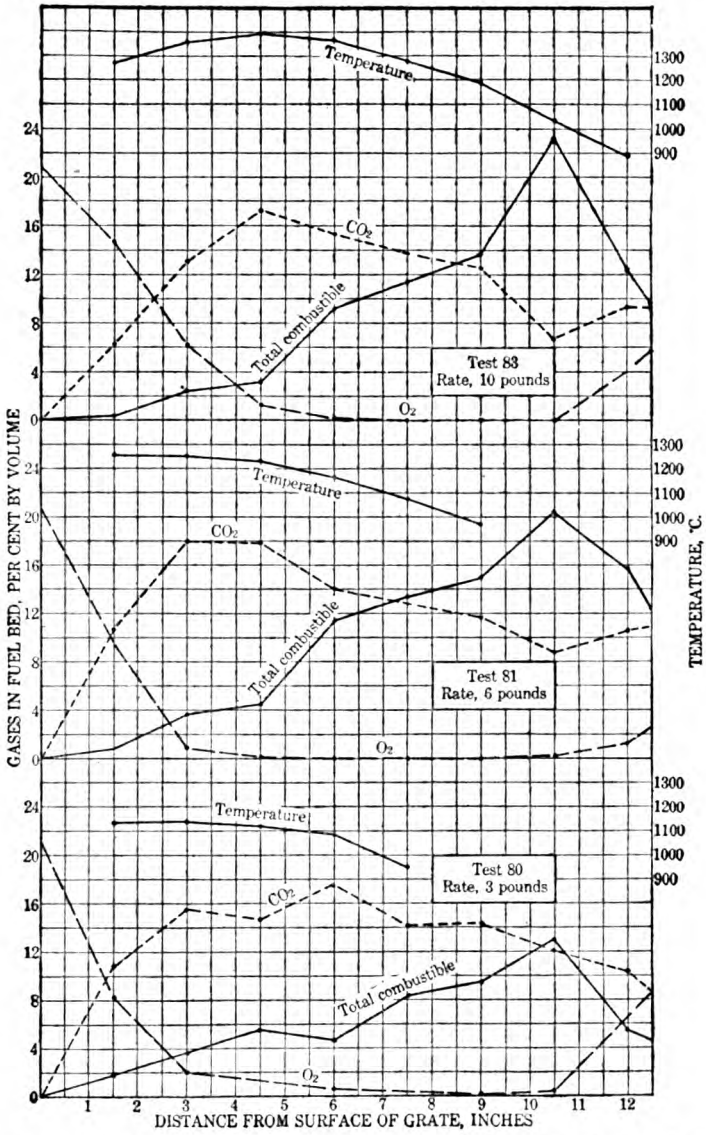

FIGURE 9.—Composition of gases and temperature in 12-inch fuel bed of metallurgica lcoke in a hand-fired experimental furnace. Rates of combustion, 10, 6, and 3 pounds of fuel per square foot of grate per hour.

rates of combustion the effects of this infiltration of air are more prominent, because the low velocity of the gases rising from the fuel bed permits more air to descend along the walls of the furnace and into the fuel bed. With the rate of combustion of 3 pounds and

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under some conditions 6 pounds of fuel per hour, enough air descends and filters through the uppermost layers to dilute the ascending gases and the CO_2 content drops instead of rising. The descent of the air could be easily noticed by the behavior of the smoke and flames above the fuel bed, and is illustrated in figure 11. It would seem that under some conditions in house-heating apparatus, when the ash pit is closed air could descend to the fuel bed through the chimney and the flue connections, and aid in the combustion.

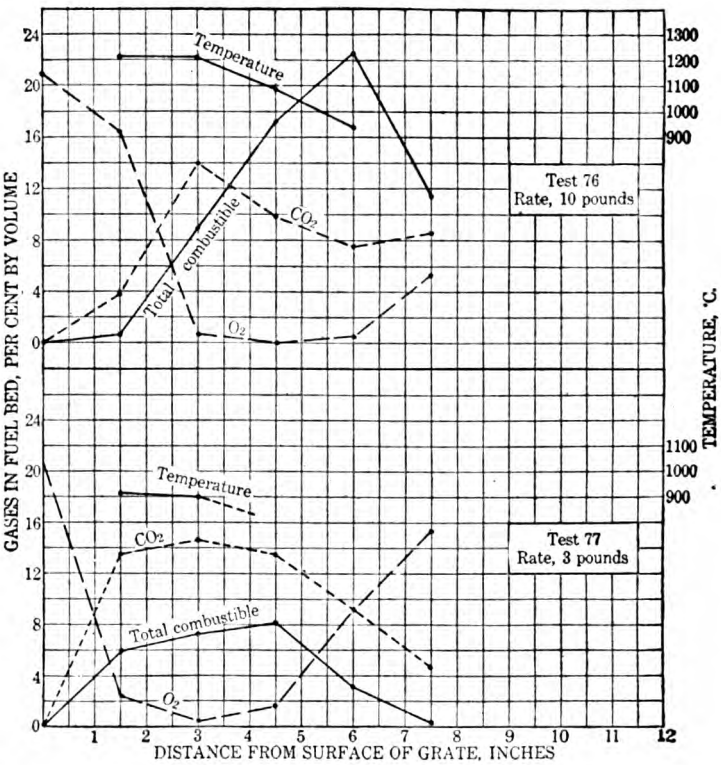

FIGURE 10.—Composition of gases and temperature in 6-inch fuel bed of semicoke in a hand-fired experimental furnace. Rates of combustion, 10 and 3 pounds of fuel per square foot of grate per hour.

With the fuel beds 12 inches thick the free oxygen from below seemed to penetrate somewhat higher than 3 inches above the grate. This was also true of the 6-inch coke bed. But in no test did free oxygen penetrate to the upper surface of the fuel bed. Hence a large part of the upper half of the fuel bed is devoid of free oxygen, and the carbon is gasified only by the reduction of CO_2.

The additional air needed to burn the large content of CO and other combustibles in the gases rising from the fuel bed may be admitted through the fire door, through cracks in the furnace, or under some

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conditions, with very low rates of combustion, by reverse currents through the chimney and the flues when the latter are large. In the tests with coke the percentage of combustible gases rising from the fuel bed was smaller than when Pittsburgh or anthracite coal was used as a fuel. Seemingly this is due to the comparative absence of hydrogen in the coke, also to the possibility that the carbon in coke is less active in reducing CO_2 than the carbon in other fuels. Comparison of figure 8, showing the composition of the gases in a coke fuel bed, with figure 10, showing similar data for a semicoke, seems to support this explanation. The semicoke retained a considerable amount of the hydrogen originally in the coal and the carbon, not being thoroughly coked, was more active in the reduction of CO_2.

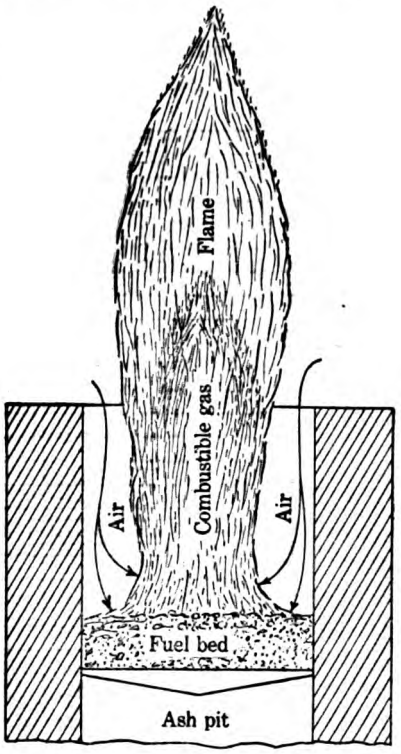

FIGURE 11.—Air flowing to the surface of fuel bed from top of furnace.

TEMPERATURE IN FUEL BED.

In figures 4 to 10, the temperatures in the fuel bed are represented by the upper curve of each figure. Generally, the temperature is higher in the lower half of the fuel bed where the fuel burns to CO_2 than in the upper half. It reaches a maximum at about the same point as the percentage of CO_2. The temperature drop in the upper half of the fuel bed is partly due to the absorption of heat by reduction of CO_2, and partly to the addition of fresh fuel, which cools the layer of burning coals immediately below.

With all fuels and with all thicknesses of fuel bed the temperature rises as the rate of combustion increases. This temperature rise is chiefly due to the fact that as the rate of combustion increases the heat is generated faster than it is dissipated from the furnace, and perhaps also to the fact that a little less air is used to gasify 1 pound of fuel at the higher rates of combustion than at very low ones.

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WEIGHT OF AIR FORCED THROUGH FUEL BED PER POUND OF FUEL GASIFIED.

The weights of air that can be forced through the fuel bed with three rates of combustion and two thicknesses of fuel bed are shown in figure 12. The dashed curves are drawn through points representing the pounds of air per pound of moisture and ash-free fuel and the solid curves through points representing the pounds of air per pound of fuel fired. The weight of air represented by the points is the quantity measured by the orifice. This quantity checks fairly closely with the figure obtained by computation from the analysis of the gases near the surface of the fuel bed before they

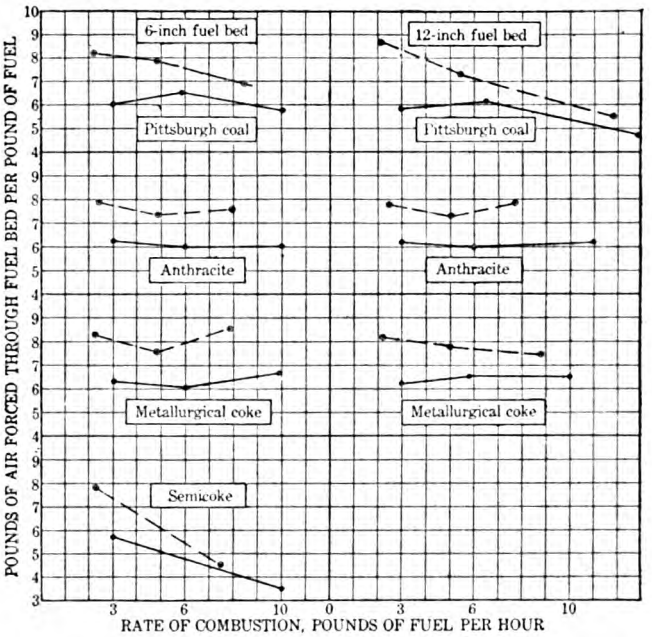

FIGURE 12.—Relation between the rate of combustion and the weight of air per pound of fuel that can be forced through the fuel bed. The left half of the figure gives data for 6-inch fuel bed and the right half for 12-inch fuel bed. The four groups of curves represent a different fuel. — — — — combustible. ———— fuel as fired.

become diluted with descending air. These computed values are given in column 22 of Table 2.

The figure shows that the weight of air per pound of fuel burned that can be forced through the fuel bed is practically independent of the rate of combustion, the kind of fuel, and the thickness of fuel bed, and that it is constant. Roughly speaking, only about 6½ pounds of air can be supplied through the fuel bed per pound of fuel fired; or, about 7 to 8 pounds of air per pound of combustible gasified. It is shown in Technical Paper 137 that the quantity of air remains nearly constant through a very wide range of combustion.

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The rate of combustion can be increased fiftyfold, from 3 pounds to 150 pounds per square foot of grate area per hour, without changing appreciably the weight of air per pound of fuel, unless there are holes in the fire, when the excess air is forced through the holes and not through the fuel bed. Any attempt to force more air through the fuel bed makes the fire burn faster, the ratio of air to a pound of fuel gasified remaining constant.

The fuel bed, then, acts as a gas producer and its object seems to be to gasify the solid fuel. A bed just thick enough to produce a maximum of CO_2 would be too thin to be practicable.

The amount of air that is forced through the fuel bed determines the rate of gasification or combustion; it does not determine the degree of completeness of combustion, which must be determined by the amount of air supplied over the fuel bed, the size of combustion space, the gas-mixing facilities, and the temperature. As previously stated, only about one-half of the air required for the complete combustion of solid fuels can be supplied through the fuel bed; the other half must be supplied over the fuel bed. In other words, only half of the process of combustion takes place in the fuel bed; the other half must take place in the combustion space above the fuel bed after sufficient air has been added to and mixed with the gases rising from the fuel bed.

RESULTS OF TESTS OF GROUP 2.

The results of the three tests of group 2 are given in Table 3, following. The tests were made with Pittsburgh coal, fired in large quantities at long intervals, as is the practice with house-heating apparatus. In conducting these tests special attention was given to the distillation process, and several sets of gas samples, as well as tar and soot samples, were collected from different points in the fuel bed during the distillation period. The analyses of each of these sets are given separately to show the progress of the distillation. For that reason the items in Table 3 are arranged in a different way than in Table 2. The following is a description of the items in the table:

Item 1 is the average rate of combustion obtained by dividing the weight of coal fired by the duration of the test in hours.

Item 2 is the duration of the test, and extends over a period of one complete firing cycle.

Item 3 is the average weight of air supplied through the grate per pound of coal burned. The value in the table is obtained by dividing the weight of air as measured with the orifice by the weight of coal burned during the test.

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TABLE 3.—*Results of tests of group 2, firing Pittsburgh coal in large quantities at long intervals.*

TEST NO. 101.

Rate of combustion.	Duration of tests.	Average weight of air supplied through grate per pound of—		Samples taken after firing.	Distance of sample from grate.	Composition of gases, per cent by volume.							Temperature in fuel bed.	Weight of air per pound of combustible.	Tar per cubic foot of gas.	Soot per cubic foot of gas.	Tar in solids.	Total combustible per cubic foot of gas.	Soot and tar in total combustible.	Unburned combustible in total combustible.	Pressure drop through fuel bed, inches of water.
		Coal.	Combustible.			CO_2.	Unsaturated hydrocarbons.	O_2.	CO.	CH_4.	H_2.	Total gaseous combustible.									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Lbs.	*Hrs.*	*Lbs.*	*Lbs.*	*H. m.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*°C.*	*Lbs.*	*Grams.*	*Grams.*	*P. ct.*	*Grams.*	*P. ct.*	*P. ct.*	
3	5	6.0	7.2	17	1.5	13.3	.....	6.6	0.4	0.2	0.0	0.6	1,104	14.6	.....	.....	.....	.....	.....	.....	.....
					4.5	15.4	0.4	.0	6.2	1.0	2.1	9.7	981	8.3	.....	.....	.....	.....	.....	.....	.....
					6.0	1.3	1.5	.....	.....	1.0	1.8	.....	770	.....	1.073	0.236	81.3	2.189	59.8	91.5	0.05
					7.5	14.6	.6	.5	6.4	3.0	3.0	13.0	290	7.5	.872	.084	90.2	4.800	19.9	56.4	.....
					9.0	5.7	.5	12.4	1.8	2.0	1.2	5.5	170	19.5	.522	.044	92.2	2.206	25.7	62.9	.....
					10.5	1.9	.1	18.1	.0	.7	.4	1.2	.....	75.5	.108	.016	87.0	.570	21.8	52.3	.....
				1 11	1.5	1.5	.....	18.7	.7	.0	.1	.8	926	.....	.....	.....	.....	.....	.....	.....	.....
					4.5	15.1	.0	4.0	1.0	.0	.0	1.0	961	12.7	.....	.....	.....	.....	.....	.....	.....
					6.0	12.0	.0	5.6	1.4	.0	.1	1.5	700	15.4	.358	.211	62.9	2.492	22.9	30.9	.....
					7.5	10.2	2.5	.1	6.5	.2	1.6	10.8	550	11.9	1.840	.179	91.1	5.326	37.9	72.7	.04
					9.0	11.3	2.7	.5	4.3	.....	.....	.....	540	.....	5.480	.344	94.1	8.954	65.1	81.9	.....
					10.5	5.0	.3	14.3	.8	.8	.0	1.9	.....	29.2	.124	.045	73.4	1.267	13.3	42.3	.....
				2 25	1.5	4.7	.....	15.8	.0	.0	.0	.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
					4.5	14.1	.0	.2	9.9	.6	.6	11.1	.....	7.8	.....	.....	.....	.....	.....	.....	.....
					6.0	14.8	.0	.2	8.7	.2	.3	9.2	815	8.2	.006	.019	24.0	3.456	.7	38.6	.....
					7.5	13.2	.1	4.7	3.5	.3	.0	3.9	875	11.7	.007	.013	35.0	2.515	.8	24.8	.02
					9.0	14.2	.0	5.1	1.9	.0	.1	2.0	830	12.5	.018	.027	40.0	2.355	1.9	13.6	.....
					10.5	6.5	.....	14.0	.4	.0	.0	.4	.....	29.3	.001	.029	3.3	1.019	2.9	8.7	.....
				4 5	1.5	3.1	.....	17.2	.3	.1	.1	.5	960	57.9	.....	.....	.....	.....	.....	.....	.....
					4.5	18.3	.....	.5	2.1	.1	.1	2.3	.....	9.9	.....	.....	.....	.....	.....	.....	.....
					6.0	16.8	.....	.1	5.9	.2	.1	6.2	.....	8.6	.004	.006	40.0	3.320	.3	27.4	.01
					7.5	14.2	.....	5.6	.9	.0	.0	.9	896	13.4	.013	.011	52.0	2.203	1.2	7.0	.....
					9.0	5.2	.....	15.2	.3	.0	.0	.3	486	36.9	.001	.001	50.0	.800	.2	6.7	.....
					10.5	2.6	.....	18.1	.0	.0	.0	.0	400	78.0	.000	.000	.....	.373	.0	.0	.....

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TEST 104.

6	3	6	7.0	8	1.5	11.2	0.0	8.7	1.2	0.0	0.1	1.3	1,084	16.3	.....	.....	.....	.....	.....	.....	.....
					4.5	15.8	.4	.0	7.2	.2	.5	8.3	1,048	8.3	.....	.....	.....	.....	.....	.....	.....
					6.0	13.5	.1	.0	10.5	1.1	2.5	14.2	.....	7.4	0.316	0.058	84.5	4.120	9.1	53.0	0.09
					7.5	13.6	1.0	.8	7.4	.1	1.7	10.2	400	8.7	1.090	.270	80.2	5.766	23.5	64.2	.....
					9.0	5.0	.4	13.2	2.3	1.1	.7	4.5	305	22.5	.313	.043	88.7	1.742	20.3	58.9	.....
					10.5	3.9	.7	14.1	2.5	1.2	1.0	5.4	200	23.6	3.060	.046	98.5	4.509	68.9	87.6	.....
				35	1.5	8.0	.1	12.0	.0	.1	.2	.4	.....	24.8	.....	.....	.....	.....	.....	.....	.....
					4.5	17.5	.5	1.2	1.1	.3	.0	1.9	.....	10.4	.....	.....	.....	.....	.....	.....	.....
					6.0	17.9	1.0	.2	1.6	1.0	1.2	4.8	.....	9.2	.104	.060	63.4	3.513	4.8	27.0	.06
					7.5	17.1	.9	.7	1.4	.0	.0	2.3	660	10.7	2.870	.120	96.0	5.943	50.3	58.5	.....
					9.0	15.7	3.8	.1	3.8	.0	.0	7.6	520	8.4	18.180	1.060	92.2	23.809	82.9	90.5	.....
					10.5	9.6	1.3	4.8	1.4	4.3	.8	7.8	660	12.0	1.420	.366	79.5	4.644	38.5	70.4	.....
				1 02	1.5	6.6	.3	13.4	.6	.1	.1	1.1	1,077	26.5	.....	.....	.....	.....	.....	.....	.....
					4.5	14.6	1.4	.2	7.0	.5	.3	9.2	913	8.3	.....	.....	.....	.....	.....	.....	.....
					6.0	15.1	.5	.3	6.9	.5	.7	8.6	.....	8.4	.023	.010	69.7	3.502	1.0	38.2	.03
					7.5	13.0	.8	.7	6.4	.0	.0	7.2	830	10.0	1.560	.173	90.0	4.782	37.3	61.0	.....
					9.0	11.6	1.6	.0	9.5	4.8	8.6	24.5	610	5.9	7.170	.250	96.6	12.104	61.4	86.3	.....
					10.5	10.8	.8	4.7	1.9	3.2	1.4	7.3	670	11.8	1.540	.223	87.4	4.500	39.1	65.6	.....
				1 37	1.5	9.1	.2	10.5	.0	.0	.1	.3	1,140	22.0	.....	.....	.....	.....	.....	.....	.....
					4.5	16.8	.0	.4	4.1	.1	.0	4.2	1,070	9.6	.....	.....	.....	.....	.....	.....	.....
					6.0	15.5	.7	3.7	.1	.2	.0	1.0	950	12.4	.002	.045	4.26	2.571	2.0	13.0	.02
					7.5	17.5	.9	1.1	.8	.1	.5	2.3	830	10.5	.029	.077	27.35	3.075	3.5	18.0	.....
					9.0	13.1	1.3	.0	6.3	.3	5.1	13.0	890	9.0	2.090	.319	85.70	5.830	41.8	67.9	.....
					10.5	9.9	.7	4.3	2.6	.9	7.1	11.2	720	13.5	.056	.089	38.60	2.473	5.9	42.5	.....

TEST 103.

10	2	6.1	7.2	11	1.5	17.2	0.0	1.6	2.5	0.0	0.1	2.6	1,140	10.2	.....	.....	.....	.....	.....	.....	.....
					4.5	11.4	.0	.1	14.6	.3	1.8	16.7	1,048	7.0	.....	.....	.....	.....	.....	.....	.....
					6.0	4.3	1.6	5.8	13.2	6.7	9.9	31.4	.....	5.8	2.280	0.285	88.8	10.328	24.9	90.3	.50
					7.5	10.3	1.5	.1	11.2	.1	.2	13.0	590	8.5	2.490	.280	89.9	8.683	32.0	72.3	.....
					9.0	11.5	.0	.6	8.9	8.7	8.4	26.0	620	5.4	1.750	.249	87.6	9.810	20.4	72.6	.....
					10.5	1.9	.4	17.6	1.1	1.8	.3	3.6	555	37.8	.768	.093	89.2	2.350	36.7	81.1	.....
				38	1.5	12.3	.0	7.4	.8	.1	.2	1.1	971	15.4	.....	.....	.....	.....	.....	.....	.....
					4.5	12.1	.0	.4	13.6	.3	1.4	15.3	.....	7.1	.....	.....	.....	.....	.....	.....	.....
					6.0	13.4	.6	.2	6.7	.3	3.8	11.4	926	9.1	.458	.254	64.3	5.344	13.3	41.4	.10
					7.5	9.4	.8	.6	12.2	5.1	12.9	31.0	890	5.5	1.110	.244	82.0	8.965	15.0	75.5	.....
					9.0	10.1	4.0	.1	8.9	.0	.0	12.9	803	8.6	17.390	.570	96.8	24.585	63.0	90.4	.....
					10.5	6.2	.2	11.8	.5	.5	.5	1.7	705	27.8	.118	.096	55.2	2.144	10.0	32.4	.....
				1 12	1.5	14.0	.0	5.7	1.1	.1	.2	1.4	1,129	12.5	.....	.....	.....	.....	.....	.....	.....
					4.5	15.0	.0	.3	8.2	.2	1.4	9.8	1,063	8.2	.....	.....	.....	.....	.....	.....	.....
					6.0	8.6	.0	11.3	.6	.0	.5	1.1	1,097	22.0	.....	.....	.....	.....	.....	.....	.05
					7.5	16.5	.0	.2	5.5	.5	1.1	7.1	885	8.9	.080	.029	73.4	5.354	2.0	27.9	.....
					9.0	11.6	.3	.4	6.1	.9	13.1	20.4	910	9.2	1.72	.209	89.2	6.903	27.5	61.2	.....
					10.5	5.7	.0	11.9	.4	.5	1.1	2.0	905	31.2	1.02	.132	88.5	2.803	41.1	52.7	.....

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Item 4 gives the average weight of air supplied through the grate per pound of moisture and ash free coal. The figure in the table was determined by dividing the weight of air per hour measured with the orifice by the weight of the combustible burned per hour. The weight of combustible was determined by multiplying the weight of coal fired by the percentage of combustible in the coal as given in Table 1, and subtracting from this the amount of combustible in the refuse.

Item 5 gives the length of time elapsed in hours and minutes between firing, and the collection of each set of samples and the temperature measurements.

Item 6 gives the position of the samplers during the collecting of gas, tar, and soot samples. The figure in the table gives the vertical distance in inches of the intake of the sampler from the grate.

Items 7 to 12 give the composition of the gas samples in percentage by volume. The constituents are indicated by their chemical symbol.

Item 13 gives the total combustible gases expressed in percentage by volume. The figures given in this item are the sums of items 8, 10, 11, and 12.

Item 14 gives the temperature in the fuel bed at the point indicated by item 6.

Item 15 gives the weight of air per pound of combustible burned, computed from the volumetric analysis of the gases.

Items 16 and 17 give the weight of tar and soot, respectively, collected per cubic foot of gas passing through the sampler at the point indicated by item 6.

Item 18 gives the percentage of tar in the combustible deposited in the sampler and the filter. The values of this item were obtained by dividing the values of item 16 by the sum of items 16 and 17, and multiplying the quotient by 100.

Item 19 gives the weight of the total combustible ingredients in the gases in grams per cubic foot of gas. This item includes the carbon of CO_2 and CO, items 7 and 10, and all of items 8, 11, 12, 16, and 17.

Item 20 shows what percentage of the original combustible ingredients leaves the solid fuel in the form of tar and soot. The values of this item were obtained by dividing the sum of items 16 and 17 by the values of item 19, and multiplying the quotient by 100.

Item 21 shows what percentage of the original combustible ingredients of the coal, item 19, leaves the solid fuel unburned or only partly burned. This item includes the carbon in the CO, as shown by item 10, and the values of items 8, 11, 12, 16, and 17.

Item 22 shows the pressure drop through the fuel bed, in inches of water.

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GRAPHIC REPRESENTATION OF RESULTS OF TESTS.

The results of the tests of group 2 are shown graphically in figures 13, 14, and 15. The left half of each figure gives the percentages by volume of oxygen, carbon dioxide, and combustible in the gases

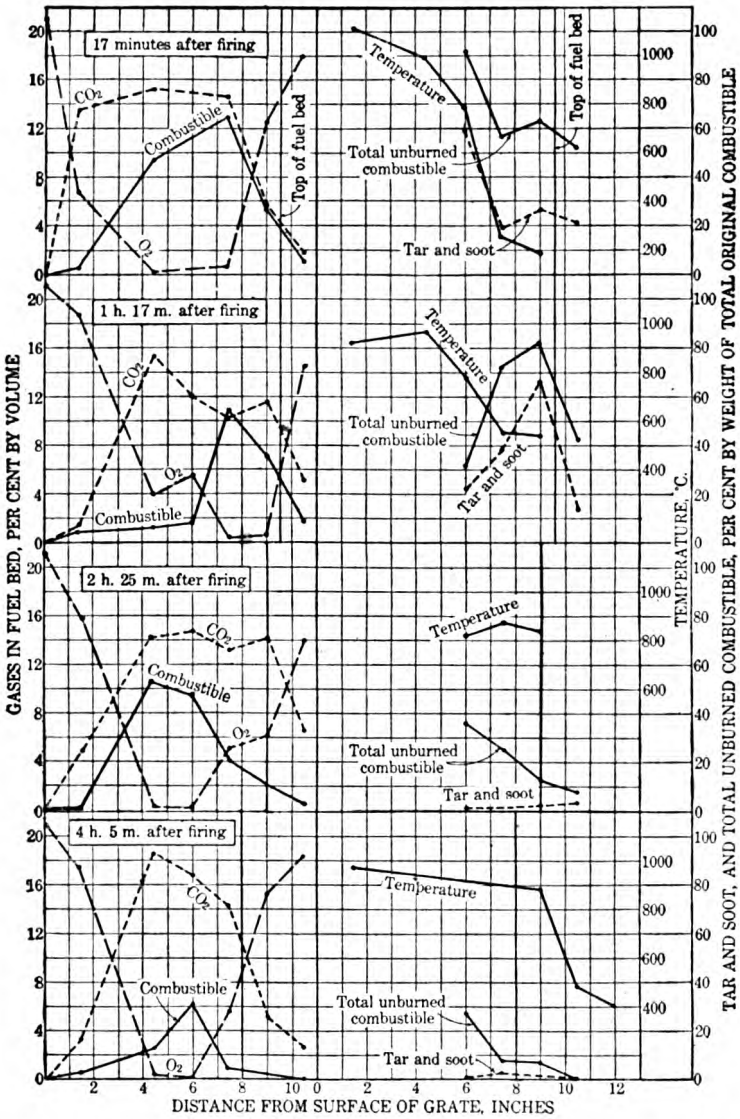
17 minutes after firing
1 h. 17 m. after firing
2 h. 25 m. after firing
4 h. 5 m. after firing
CO2
Combustible
O2
Top of fuel bed
Temperature
Total unburned combustible
Tar and soot
GASES IN FUEL BED, PER CENT BY VOLUME
TEMPERATURE, °C.
TAR AND SOOT, AND TOTAL UNBURNED COMBUSTIBLE, PER CENT BY WEIGHT OF TOTAL ORIGINAL COMBUSTIBLE
DISTANCE FROM SURFACE OF GRATE, INCHES

FIGURE 13.—Results of test 101. Pittsburgh bituminous coal; rate of combustion, 3 pounds of coal per square foot of grate per hour. Curves at left show variation in composition of gases in fuel bed at different intervals after a large firing; curves at right show variation in the percentage of total unburned combustible and of the tar and soot based on total weight of combustible leaving the fuel, consisting of the carbon in CO_2 and CO, and all of the H_2, CH_4, unsaturated hydrocarbons, tar, and soot. The unburned combustible includes all of these except the carbon in CO_2, hence the difference between the ordinates of its curve and 100 per cent represents the carbon completely burned to CO_2.

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within the fuel bed at various distances above the grate at different periods of the firing cycle. The time of taking the samples is stated at the top of each group of curves. The right half gives for the same periods of the firing cycle the content of unburned combustible expressed as percentage by weight of the original combustible ingre-

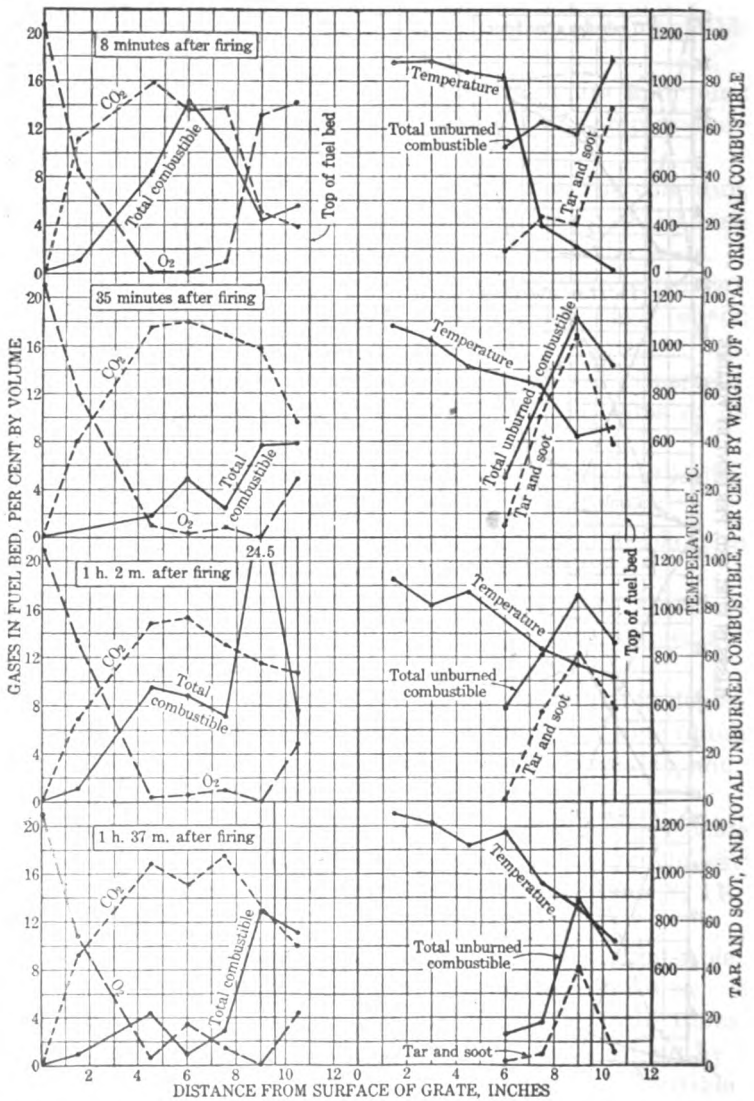
8 minutes after firing
35 minutes after firing
1 h. 2 m. after firing
1 h. 37 m. after firing
CO2
O2
Total combustible
Top of fuel bed
Temperature
Total unburned combustible
Tar and soot
24.5
GASES IN FUEL BED, PER CENT BY VOLUME
TEMPERATURE, °C.
TAR AND SOOT, AND TOTAL UNBURNED COMBUSTIBLE, PER CENT BY WEIGHT OF TOTAL ORIGINAL COMBUSTIBLE
DISTANCE FROM SURFACE OF GRATE, INCHES

FIGURE 14.—Results of test 104. Pittsburgh bituminous coal; rate of combustion, 6 pounds of coal per square foot of grate per hour. Curves at left show variation in composition of gases in fuel bed at different intervals after a large firing; curves at right show variation in the percentage of total unburned combustible, and of the tar and soot based on weight of the total combustible leaving the fuel, consisting of the carbon in CO_2 and CO, and all of the H_2, CH_4, unsaturated hydrocarbons, tar, and soot. The unburned combustible includes all these except the carbon in CO_2, hence the difference between the ordinates of its curve and 100 per cent represents the carbon completely burned to CO_2.

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dients in the coal, and the percentage of tar and soot combined. These two curves are the graphs of items 20 and 21 of Table 3. The solid curve represents the temperature changes.

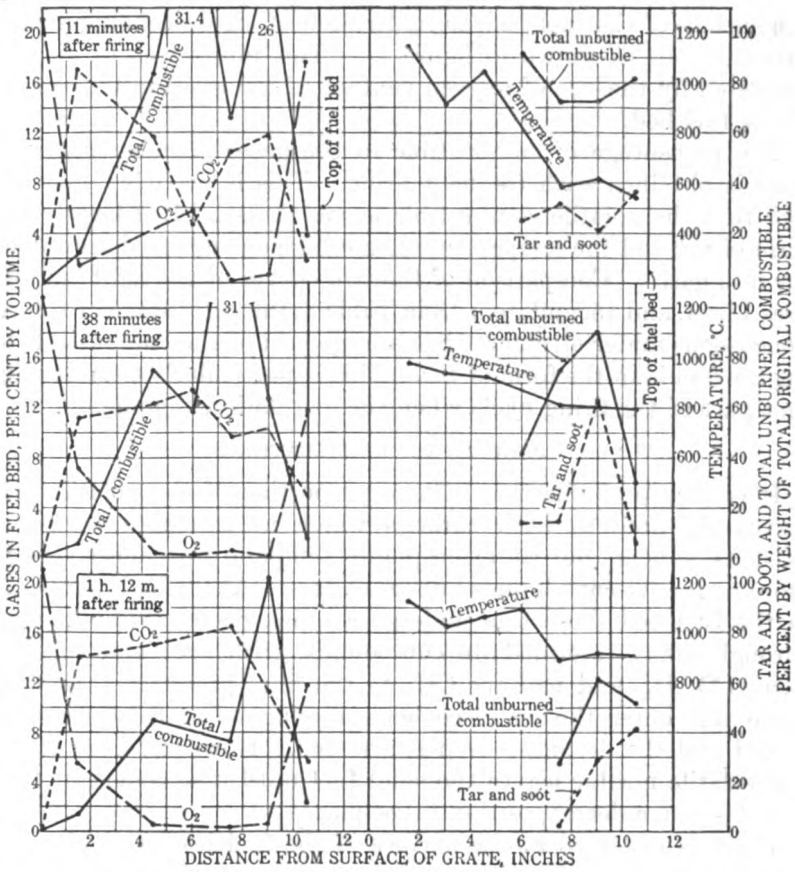

FIGURE 15.—Results of test 103. Pittsburgh bituminous coal; rate of combustion, 10 pounds of coal per square foot of grate per hour. Curves at left show variation in composition of gases in fuel bed at different intervals after a large firing; curves at right show variation in the percentage of total unburned combustible and of the tar and soot based on weight of total combustible leaving the fuel, consisting of the carbon in CO_2 and CO, and all of the H_2, CH_4, unsaturated hydrocarbons, tar, and soot. The unburned combustible includes all of these except the carbon in CO_2, hence the difference between the ordinates of its curve and 100 per cent represents the carbon completely burned to CO_2.

DISCUSSION OF RESULTS.

The thickness of the fuel bed was not constant in this group of tests; it was 10 to 12 inches immediately after firing and decreased as the fuel burned away. The change of thickness is indicated in figures 13, 14, and 15 by the difference of position of the vertical lines representing the top of the fuel bed.

The composition of the gases in the fuel bed shows the same characteristics as in the tests of group 1, which were made with small firings at frequent intervals. The free oxygen is all used up at a

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point 4½ inches above the surface of the grate. The CO_2 content reaches a maximum at this point, and then decreases as the gases flow through the upper layers of the fuel bed. As previously stated, this decrease is due to reduction to CO by the hot carbon, and, near the surface of the fuel bed, to infiltration of air descending along the furnace walls as shown in figure 11. This infiltration of air is also indicated by the rise of oxygen content of the gases near the surface of the fuel bed.

The percentage of combustible in the gases is somewhat smaller than is obtained with frequent firing. This is probably due to the fact that the volatile combustible leaves the solid fuel largely in the form of tar and the temperature is not high enough to decompose the tar into gases. Comparison of the two curves of the right half of figures 13, 14, and 15, and item 18 in Table 3, the percentage of tar in the nongaseous material, shows that a large part of the combustible leaving the fuel is in the form of tar. This is particularly true during the first part of the firing cycle when the distillation is going on.

PROCESS OF DISTILLATION.

It is very probable that a large proportion of the volatile matter leaves the coal as hydrocarbons which at the high temperature exist as vapors, but at atmospheric temperature collectively form more or less viscous liquids known as tars. At the high temperature in the fuel bed these tars undergo a quick decomposition, possibly through many intermediate compounds, with soot and the simple gases CO, H_2, and perhaps CH_4 as the final products. As soon as these tars enter the water-cooled sampling tubes they are quickly cooled and the decomposition is arrested. However, from the time the volatile matter leaves the solid fuel until it is cooled in the gas samples, some decomposition takes place.

The tars collected at the surface of the fuel bed, 1½ inches below the surface, and 1½ inches above it were accumulated after being extracted with benzol, and were subjected to fractionation by distillation. Table 6 gives the results of this fractionation. As a total of only 64 grams of material was available the figures given have only a qualitative value.

TABLE 4.—*Results of fractionation of tars collected in fuel bed of experimental hand-fired furnace.*

Temperature of distillation.	Distillate.	Color.	Remarks.
°C.	*Per cent.*		
100–120	[a] 11.55	Yellow, then red by oxidation	Thin liquid.
120–170	[a] 6.07	do	Do.
170–200	.10	Yellow, then black by oxidation	Do.
200–210	.03	do	Do.
210–235	.47	do	Do.
235–270	3.05	do	Do.
270–315	16.25	do	Do.
315–355	7.27	Dark yellow, then black by oxidation	Do.
Above 355	55.25	Black, solid and somewhat plastic	

[a] Mostly the added benzol.

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Analysis of the largest fraction, distilled at 270° to 315° C., gave the following composition: Carbon, 85.7 per cent; hydrogen, 9.6 per cent; and oxygen, 4.7 per cent. This composition gives the empirical formula $C_6H_8O_{0.25}$. The specific gravity was 0.970. By analysis 10.1 c. c. of material yielded 2.5 c. c. tar acids, 2.5 c. c. unsatu-

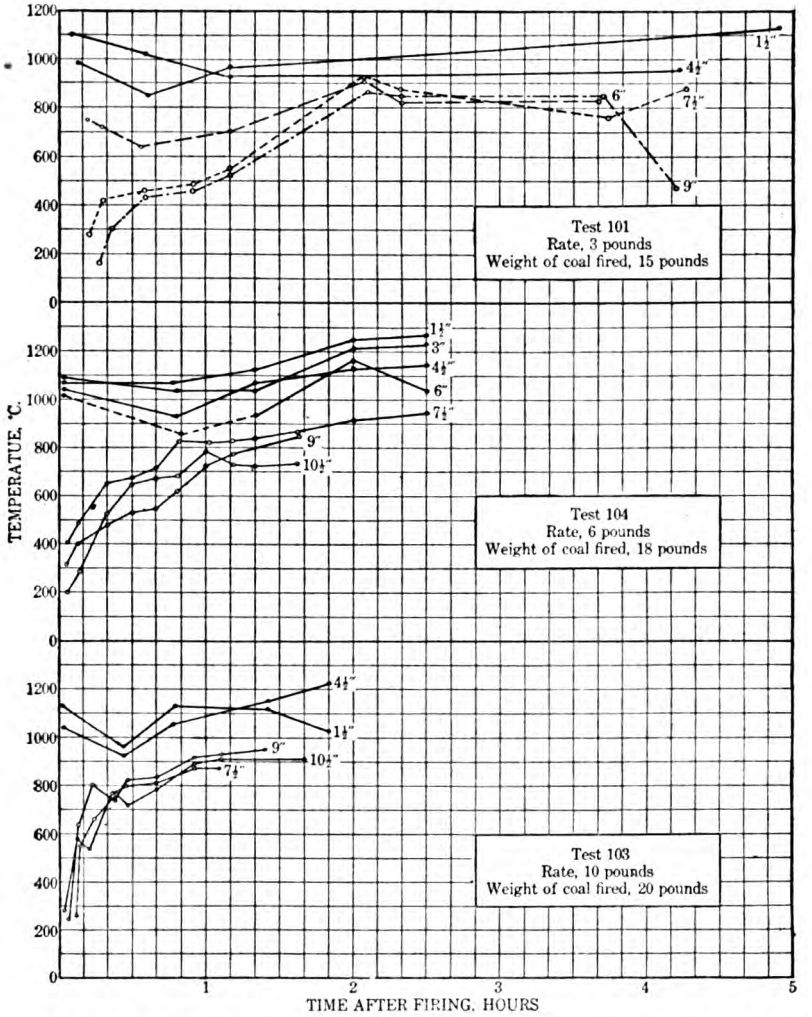

FIGURE 16.—Effect of the rate of combustion on the rate of heating of freshly fired coal. The figure near each curve indicates the vertical distance in inches above the grate of the point where temperatures were taken. Solid circles represent temperatures of the coke residue obtained with optical pyrometer; open circles represent temperatures of the freshly fired coal obtained with Hoskin thermocouples buried at different depths in the coal.

rated aliphatic bodies, 1.5 c. c. paraffins. The remaining 3.6 c. c. includes the aromatic hydrocarbons and the material lost in the operations. No naphthalene or anthracene could be found.

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The fractional distillation shows that at atmospheric temperature roughly about one-half of the tar substance is in the liquid state.

Each of the distillates is not one chemical compound, but is a mixture probably of a large number of compounds. These compounds consist mainly of carbon and hydrogen, although some of them have a small percentage of oxygen. The formula as given in the paragraph following Table 4 represents the average composition of the compounds in the fraction distilled at 270° to 315° C. The other distillates probably have different average compositions. Table 4 with Table 3 shows that the combustion in the fuel bed consists of a large number of simultaneous as well as consecutive reactions, which form a vastly complex reaction system.

RATE OF HEATING OF FRESHLY FIRED COAL.

The rate of heating of the freshly fired coal is shown graphically in figure 16. The solid black circles indicate the temperatures in the hot coke obtained with the optical pyrometer, and the open circles indicate the readings taken with three Hoskin thermocouples buried at different depth in the freshly fired coal. The figure near each curve indicates the distance in inches from the grate of the points where the temperatures were taken. The temperatures were taken as described on page 13.

The uniform rise of temperature in the freshly fired coal as shown by all three thermocouples indicates that the coal is heated mostly by the hot gases streaming up through it, and only to a small extent by contact with the hot coke. As a result the rate of heating increases rapidly with the rate of combustion. Thus, at a rate of combustion of 3 pounds the coal is heated from about 200° C. to 850° C. in about two hours, at a rate of combustion of 6 pounds, in about one hour, and at a rate of 10 pounds in less than half an hour.

TESTS OF GROUP 3.

PURPOSE AND METHOD OF CONDUCTING TESTS.

The object of the third group of tests was to study the processes of combustion in the fuel bed when the admission of air through the grate was entirely stopped, and to determine whether the fire could be kept burning for a length of eight hours or more under such conditions. The conditions are somewhat similar to those in house-heating apparatus when fires are kept over night.

The tests were started by building a hot bed of coals with a given fuel to the desired thickness, enough air being supplied through the fuel bed for a rate of combustion of about 15 pounds. The admission of air under the fuel bed was then shut off by plugging the orifice with a rubber stopper. Then samples of gas were collected and tempera-

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tures in the fuel bed were measured in the usual manner. In the first few tests of this series attempts were made to measure the temperature with an optical pyrometer, but the temperatures soon became too low for reading with this instrument. Therefore the color of the fuel bed was noted as, for instance, "nearly black," or "black." In subsequent tests the temperatures were measured with a Hoskins thermocouple made of wires about one-eighth of an inch thick. The couple was inserted about 8 inches into the fuel bed through the gas sampling holes in the side of the furnace. While the temperature was being measured, leakage around the couple was prevented with asbestos packing. This method of temperature measurement was necessarily slower than with the optical pyrometer, because time had to be given for the couple to become heated to the temperature of the fuel bed.

NOTES ON INDIVIDUAL TESTS OF GROUP 3.

TEST 86, PITTSBURGH COAL, 12-INCH FUEL BED.

The fire was started at 8.55 a. m. and the fuel bed was gradually built to 12 inches. At 10.31 the ash pit was cleaned and the air supply through the grate was completely shut off. The top of the furnace was left open so that air could descend freely to the fuel bed from the top. The fuel bed gradually settled and in order to keep its thickness at 12 inches, 1 pound of coal was spread over the surface of the fuel bed at 10.46, 11.15, 11.45, and 12.30. At 1.30 the fuel bed was dull red at 1½, 3, and 4½ inches above the grate and was black at 6 inches above the grate, showing that the bed was cooling from the top. At 2.30 there was a faint glow only at 4½ inches from the grate, the rest of the fuel bed appeared black. At 3.30 the entire fuel bed appeared black. Gas samples were collected at 10.47, 11.59, and 1.42. The composition of the samples is shown graphically by the upper group of curves in figure 17 (p. 46).

TEST 88, ANTHRACITE COAL, 12-INCH FUEL BED.

The fire was started at 8.30 a. m. and the fuel bed was gradually built to 12 inches. At 10.09 a. m. the ash pit was cleaned and the supply of air through the grate was completely shut off. The top of the furnace was left open. To keep the thickness of fuel bed at 12 inches, 1 pound of coal was spread over its surface at 10.20, 10.50, 11.20, 11.50, and 1.10 a. m. At 2.30 there was a red glow only at 4½ inches from the grate, all the rest of the fuel bed was dark. At 3.30 the fuel bed was dark all over. Gas samples were collected at 10.37, 1.26, and 2.02, the analyses being given by the middle group of curves in figure 17.

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TEST 89, METALLURGICAL COKE, 12-INCH FUEL BED.

The fire was started at 8.50 a. m., and the fuel bed was gradually built to 12 inches. At 10.40 the air supply through the grate was completely shut off; no fuel was added during this test. At 1.45 the entire fuel bed appeared dark. Samples of gases were taken at 10.45, 12.02, and 1.20. The analyses of these samples are shown by the lower group of curves in figure 17.

TEST 100, PITTSBURGH COAL, 18-INCH FUEL BED.

The fire was started at 8.15 a. m. and the fuel bed was gradually built up to 18 inches. At 9.42 a. m. the supply of air through the grate was completely shut off. No coal was fired during this test. At 5.45 p. m. the fuel bed was still hot. At 9.40 a. m. the next day after the air had been completely shut off for 24 hours, air was supplied through the grate and the fire was readily started. Four sets of gas samples and temperature measurements were taken in this test. The composition of the gas samples and the temperature measurements are shown graphically by the curves of the upper group in figure 18 (p. 47).

TEST 99, ANTHRACITE COAL, 18-INCH FUEL BED.

The fire was started at 8.30 a. m. and the fuel bed was gradually built up to 18 inches. At 10.18 a. m. the air supply through the grate was completely shut off. Four sets of gas samples and temperature measurements were taken. The last set was taken at 7.31 p. m., at which time the bottom part of the fuel bed was still red hot and by supplying air through the grate the fire could be started readily. The next morning, 14 hours later, the fuel bed was black and apparently the fire was out. The composition of the gas samples and the temperature measurements are shown graphically by the middle group of curves in figure 18.

TEST 96, METALLURGICAL COKE, 18-INCH FUEL BED.

The fire was started at 8.12 a. m. and the fuel bed built to 18 inches. At 9.16 a. m. the air supply through the grate was completely shut off. Four sets of gas samples and temperature measurements were taken, the last one being taken at 3.05 p. m., at which time the entire fuel bed was dark; apparently the fire was out. The composition of the gas samples and the temperature measurements are shown graphically by the lower group of curves in figure 18.

TEST 97, METALLURGICAL COKE, 18-INCH COKE BED COVERED WITH 2-INCH LAYER OF BITUMINOUS SLACK.

The fire was built with coke to a thickness of 18 inches. At 9.14 a. m. the fuel bed was covered with a layer of bituminous slack and the air supply through the grate was completely shut off. Gas sam-

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ples and temperature measurements were taken at 9.20 a. m., 11.15 a. m., 1.10 p. m., and 3.10 p. m. At 4.30 p. m. the fuel bed was still red hot. Next day at 11.25 a. m., 26 hours after the air was shut off, the fuel bed was still hot and when air was admitted through the grate, all the fuel was brought to red heat in 35 minutes. The analyses of the gas samples and the temperature measurements are shown graphically by the upper group of curves in figure 19 (p. 48).

TEST 98, METALLURGICAL COKE, 18-INCH COKE BED COVERED WITH 2-INCH LAYER OF ASHES.

The fire was built to 18 inches. At 9.36 a. m. the air supply through the grate was shut off and the fuel bed covered with a 2-inch layer of fine dry ash. At 3 p. m. the fuel 9 inches from the grate glowed slightly; all the rest of the fuel bed was black. At 4.45 p. m. air was again supplied through the grate, but the fire would not start. Four sets of gas samples and temperatures were taken at 9.50 a. m., 1. 24 p. m., 2.58 p. m., and 4.30 p. m. The analyses and the temperature measurements are shown graphically by the lower group of curves in figure 19.

TEST 97–A, METALLURGICAL COKE, 18-INCH COKE BED COVERED WITH 2-INCH LAYER OF BITUMINOUS SLACK.

This test was a check on test 97. The object was to determine whether an 18-inch bed of coke covered with a 2-inch layer of bituminous slack would remain burning when the air supply through the grate was completely shut off and the fuel bed was not disturbed by gas samplers as in test 97. The fire was started at 10.30 a. m. and built to 18 inches. At 11.20 the fuel bed was covered with a 2-inch layer of bituminous slack and the air supply through the grate was completely shut off. No gas samples and temperature measurements were taken. At 3 p. m. smoke was issuing from the top of the fuel bed. At 4.30 p. m. the smoking stopped. At 9.40 p. m. the fire was completely out and the fuel bed was cold. The bituminous slack coal was caked where it came in contact with the hot coke, but at the surface it was not changed appreciably.

TEST 97–C, METALLURGICAL COKE, 12-INCH FUEL BED WITH NO COVERING.

The object of this test was to determine whether a coke fire will remain burning when air is admitted beneath the grate through only a 1-inch circular hole and with very low natural draft. The fire was started with wood shavings and coke by the use of forced draft. At 10.30 a. m. the forced draft was shut off and air under natural draft allowed to enter through the 1-inch orifice, all other openings being closed. The pressure drop through the orifice was about 0.01 inch of water measured with an incline gage. No gas samples were taken

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during this test. After 24 hours the forced draft was put on again and flames appeared at the surface of the fuel bed in 6 minutes, showing that the fire kept burning with the small air supply through the grate.

GENERAL DISCUSSION OF RESULTS OF TESTS.

Most of the results of this group of tests are shown graphically in figures 17, 18, and 19.

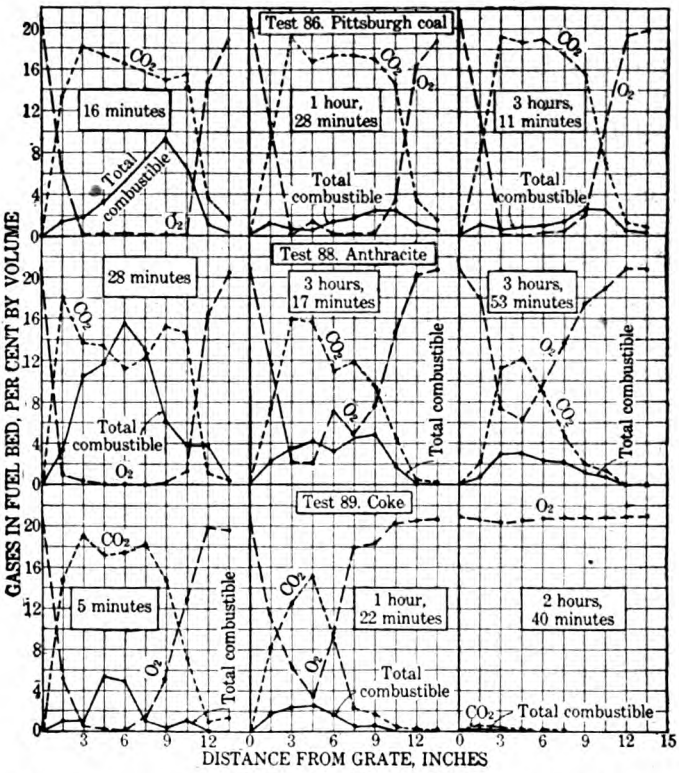

FIGURE 17.—Effect of shutting off completely the air supply through grate on the composition of gases in 12-inch fuel beds. The figures in hours and minutes represent the time that elapsed between shutting off air and taking samples.

In none of the three tests made with a 12-inch fuel bed of Pittsburgh coal, anthracite coal, and metallurgical coke—tests 86, 88, and 89 (p. 43 and fig. 17)—did the fire last five hours, although with Pittsburgh coal it lasted much longer than with coke. The composition of gases as given in figure 17 indicates that cooling of the fire was mostly from the top and the fuel bed of coke cooled the most quickly.

In the three tests with similar fuels and a fuel bed 18 inches thick—tests 100, 99, and 96 (p. 44 and fig. 18)—the Pittsburgh coal remained burning more than 24 hours and the anthracite coal 9 hours, indicating that both coals would keep fire over night. The coke fire

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lasted less than 3 hours, proving that it is impossible to keep fire over night with coke when the air through the grate is completely shut off.

It was thought that if the fuel bed of coke were covered with a layer of bituminous slack rapid cooling could be prevented and the fire

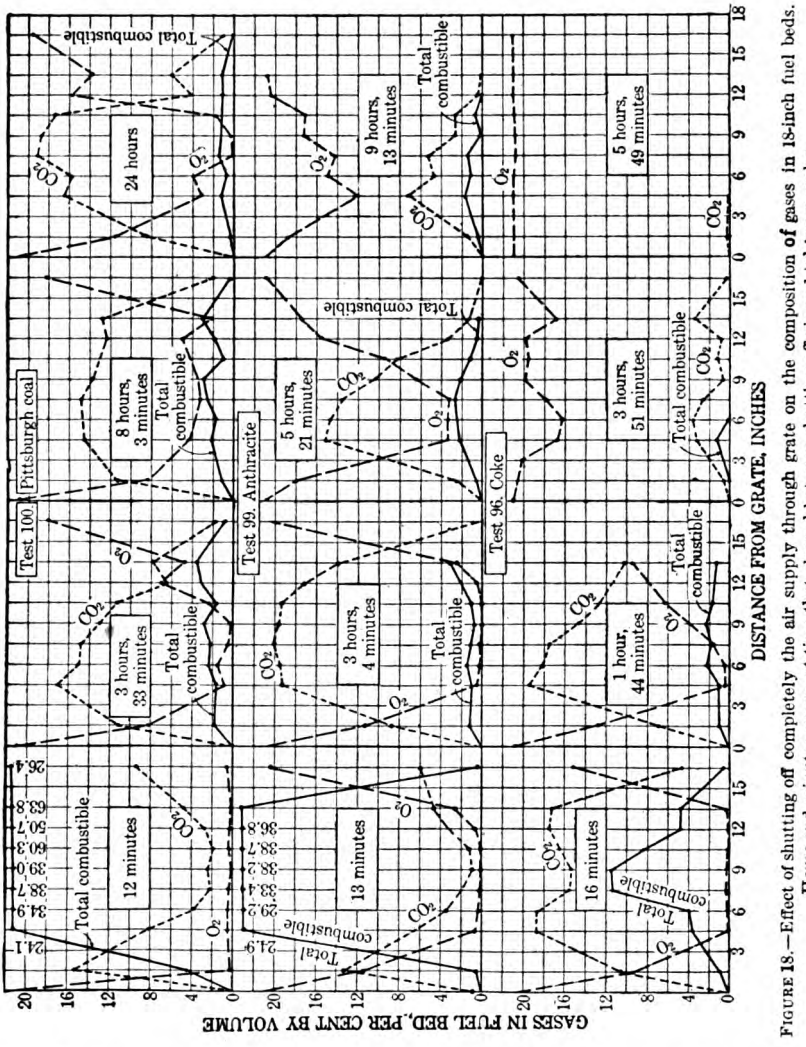

FIGURE 18.—Effect of shutting off completely the air supply through grate on the composition of gases in 18-inch fuel beds. Hours and minutes represent time that elapsed between shutting off air and taking samples.

might be kept overnight. Such a test (No. 97) is described on page 45 and illustrated in figure 19. The fire kept more than 24 hours.

Test 98 (p. 45 and fig. 19), which was run with a layer of ashes covering the fuel bed, in order to determine whether preventing of the fire from cooling or the sifting of the bituminous slack into the fuel bed kept the fire burning. The fire went out in about three hours, showing that prevention of cooling will not preserve the fire.

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Evidently in test 97 some of the bituminous slack was shaken down into the fuel bed while the gas samples were being taken, also the leakage of air through the sampling holes while the gas samplers were being inserted and removed helped to keep the fire burning.

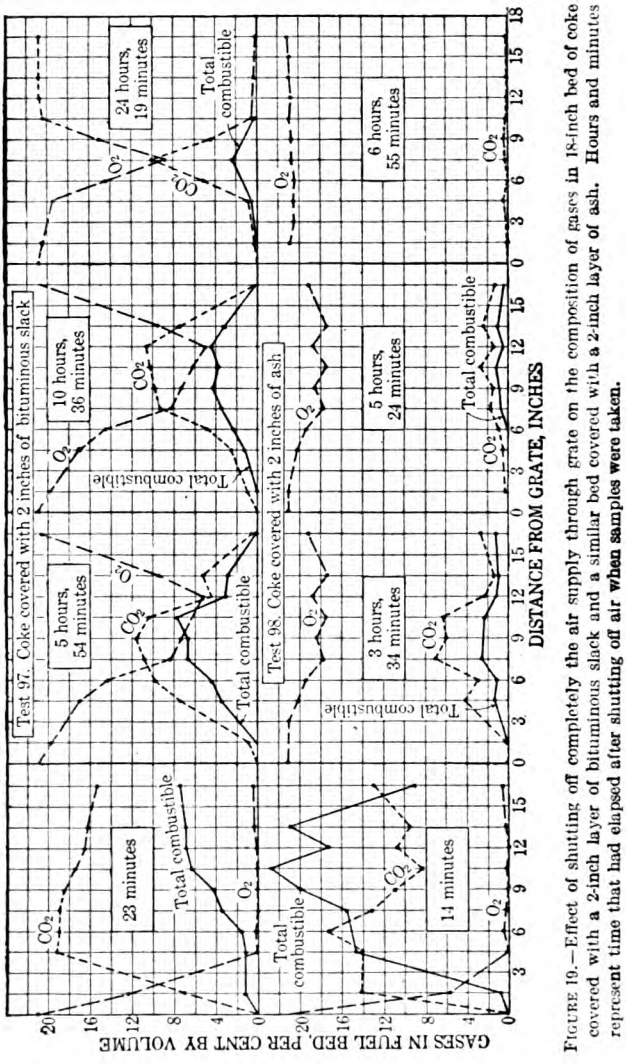
Test 97. Coke covered with 2 inches of bituminous slack
23 minutes
5 hours, 54 minutes
10 hours, 36 minutes
24 hours, 19 minutes
Test 98. Coke covered with 2 inches of ash
14 minutes
3 hours, 34 minutes
5 hours, 24 minutes
6 hours, 55 minutes
Total combustible
CO2
O2
CO
GASES IN FUEL BED, PER CENT BY VOLUME
DISTANCE FROM GRATE, INCHES

FIGURE 19.—Effect of shutting off completely the air supply through grate on the composition of gases in 18-inch bed of coke covered with a 2-inch layer of bituminous slack and a similar bed covered with a 2-inch layer of ash. Hours and minutes represent time that had elapsed after shutting off air when samples were taken.

In addition, while the gas samples were being taken the gases drawn from the fuel bed were replaced by a rapid infiltration of several cubic feet of air which probably materially aided in preserving the fire. On the other hand, the water-cooled gas samplers probably conducted enough heat away to partly compensate for such changes. To determine the effects of these factors, no gas samples were taken in test 97–a, so that the fuel bed was not disturbed. Other conditions

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were the same as in test 97. The fire apparently went out in about six hours, showing that the disturbance of the fuel bed and the infiltration of air brought about by the sampling of gases were important factors in keeping the fire going in test 97. The same is true of all the tests in which samples of gas were taken.

The effect of a small air supply through the fuel bed is shown by test 97–c. In this test a very small quantity of air was introduced through the grate. Although the bed was only 12 inches thick and had no covering, the fire was easily kept for more than 24 hours.

It is safe to state, therefore, that with the air supply through the grate completely shut off it is practically impossible to keep fire overnight. A small supply of air through the grate will help greatly to keep the fire going without burning the fuel out entirely, even when metallurgical coke is used as fuel. It should be remembered that in commercial house-heating apparatus it is practically impossible to shut off the air supply through the grate completely, because the ash-pit door, with its damper shutters and other accessories, never fits tightly, so that there may easily be an opening equivalent to a circular hole 1 inch in diameter and enough air may enter the ash pit to keep up slow combustion. If there is trouble from the bed burning out overnight when the ash-pit doors are closed, it is evident that an undue amount of air leakage under the grate is responsible. This shows the necessity of providing an air-tight ash-pit connection with the floor and the first section of the boiler and tight-fitting ash-pit doors so that the air can be controlled as desired.

CONCLUSIONS.

The conclusions from all three groups of tests have been given on pages 9 to 11 and need not be repeated here.

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